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# THEORETICAL PHARMACEUTICAL CHEMISTRY

BY

C. G. LYONS, M.A., PH.D., F.R.I.C.

AND

F. N. APPLEYARD, B.SC., PH.C., F.R.I.C.

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# PREFACE

THIS book represents an attempt to approach the teaching of pharmaceutical chemistry from a systematic scientific point of view. The inclusion of the essential principles of physical, inorganic and organic chemistry within the confines of a single volume of reasonable size has necessitated considerable compression, and the exclusion of all matter that did not seem directly connected with the general principles or the pharmaceutical aspects of chemistry. In particular, certain aspects of physical chemistry have been dealt with somewhat briefly. It is hoped that this presentation will enable the student to acquire a general knowledge of those fundamental chemical principles which form the basis of pharmaceutical chemistry.

For this edition the text has been thoroughly revised, extended, and partially rewritten.

Grateful recognition is made for the suggestions received during preparation of the manuscript from Mr. F. H. Oliver, B.Sc., B.Pharm.

C. G. L.
F. N. A.

PORTSMOUTH MUNICIPAL COLLEGE
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## SECTION I

# THEORETICAL AND PHYSICAL CHEMISTRY

# CHAPTER I

## THE ATOMIC AND MOLECULAR THEORIES

THE early workers in chemistry found that some substances (called *elements*) could not be broken up by chemical reactions into simpler substances, but that the more complex substances (called *compounds*) formed by the combination of elements in various proportions could be broken up into their constituent elements.

The *laws of chemical combination* were discovered as the result of investigations into the proportions by weight and by volume in which the elements and compounds react together.

*The law of conservation of mass* states that the total mass of the substances taking part in a chemical reaction is equal to the total mass of the products formed by the reaction.

*The law of definite proportions* states that a given chemical compound, however it is prepared, always contains the same elements combined together in the same proportions by weight, i.e. a compound, however prepared, has a fixed and invariable composition.

*The law of multiple proportions* states that when two elements combine to form more than one compound, the weights of the one element which combine with a certain weight of the other bear a simple arithmetical relation to one another. For example, copper combines with oxygen to form two compounds. In the one (cupric oxide), 1 g of oxygen combines with 3·974 g of copper, while in the other (cuprous oxide) 1 g of oxygen combines with 7·948 g of copper. These weights are in the simple ratio 1 : 2.

### Equivalent Weights

Further investigations showed that when one element replaced another element to form a new compound, the weight of the one element replacing a definite weight of the other had certain constant values. A definite weight of the one element is chemically *equivalent* to a certain weight of the other.

For example, it was found that when magnesium replaced the hydrogen of acids to form salts, this replacement always took place in the ratio 12·07 g of magnesium to 1 g of hydrogen. 12·07 g of magnesium are chemically equivalent to 1 g of hydrogen. Similarly it was found that 35·2 g of chlorine are chemically equivalent to 1 g of hydrogen.

A large number of these *equivalent or combining weights* were determined, and it was found that the equivalent weights of the elements with reference to a particular element (e.g. hydrogen) represented their combining ratios with other elements.

For example, when magnesium and chlorine combine to form magnesium chloride, they do so in the ratio 12·07 g of magnesium to 35·2 g of chlorine, i.e. in the ratio of their equivalent weights with reference to hydrogen.

When the equivalent weight of any element has been determined accurately, by very careful chemical analysis of a few compounds, this value can be used to calculate the exact composition of all the other compounds of the element.

At first, equivalent weights were calculated with reference to hydrogen, but later it was found more convenient to calculate them with oxygen as the basis (cf. p. 5). *The equivalent weight of an element* is defined as *the number of parts of the element which combines with or replaces eight parts by weight of oxygen.*

Some elements have more than one equivalent weight. The values of these equivalent weights generally bear a simple arithmetical relationship to one another. For example, the equivalent weights of sulphur in hydrogen sulphide and sulphur dioxide are 16·04 and 8·02 respectively. These values are in the simple ratio 2 : 1.

The relationships between the equivalent weights of the elements are embodied in the *law of reciprocal proportions* which states that if two elements combine not only with one another but also with a third element, then the weights of the elements combining with a fixed weight of the third element are in a simple relationship with the weights in which they combine with one another.

For example—

1 part by weight of hydrogen combines with 7·94 parts of oxygen to form water.

7·94 parts by weight of oxygen combine with 8·02 parts of sulphur to form sulphur dioxide.
1 part by weight of hydrogen combines with 16·04 parts of sulphur to form hydrogen sulphide.

Thus the equivalent weights of sulphur are in the ratio 8·02 : 16·04 = 1 : 2.

## THE ATOMIC THEORY

The experimental facts summarized in the laws of chemical combination were explained by *Dalton* in 1802 by assuming that matter, although divisible to an extreme degree, is not infinitely divisible. The smallest possible particle was called the *atom*. Dalton's theory may be outlined as follows*—

(1) Atoms are indivisible, and cannot be created or destroyed.

(2) All the atoms of a particular element are identical, but the atoms of different elements have different properties.

(3) Compounds are formed by the union of the atoms of the elements.

When atoms combine they often do so in simple numbers, e.g. 1 atom of A with 1 or 2 atoms of B. The particle formed by the union of two or more different atoms was called by Dalton a *compound atom*. It is now usually called a *molecule* (cf. p. 8).

### Atomic Weights

The earliest atomic weights were calculated with reference to hydrogen as the standard (H = 1), as the hydrogen atom is the lightest atom of any element. Later oxygen was chosen as the standard (O = 16). *The atomic weight of any element* may be defined as *the weight of the atom of the element relative to one-sixteenth the weight of the oxygen atom.* On this scale, the atomic weight of hydrogen is 1·0078. The most recent values for the atomic weights of the elements are shown in the table facing p. 302.

The numerical value of the atomic weight of an element is related to its equivalent weight. For example, if an element X of atomic weight A (H = 1) combines with hydrogen in the ratio of one atom of X to $n$ atoms of hydrogen (i.e. to form the compound $XH_n$), then A parts by weight of X combine with $n$ parts by weight of hydrogen, i.e.

---

* These simple statements require slight modification in view of the comparatively recent discovery of radioactivity and isotopes.

$$\text{Atomic weight} = \text{equivalent weight} \times n$$

The number $n$, which represents the number of atoms of hydrogen which combine with (or replace) one atom of the element is called the *valency* of the element.

$$\text{Atomic weight} = \text{equivalent weight} \times \text{valency.}$$

## EXPERIMENTAL DETERMINATION OF ATOMIC WEIGHTS

The experimental determination of the atomic weight of an element depends on the accurate determination of the equivalent weight. This is obtained as the result of a series of careful measurements of the weight in which the element combines with or displaces a known weight of hydrogen, oxygen, or in many cases, such other elements as chlorine, sulphur, or silver, whose equivalent weights have been determined previously. The materials used must be subjected to a very careful purification, and this and the actual measurements require a very high standard of manipulative technique, in order to obtain a result of a high order of accuracy.

The atomic weight of the element is an integral multiple of its equivalent weight, and the value of the integer is obtained from one of the following considerations—

(1) *Dulong and Petit's Rule.* The product of the atomic weight and the specific heat of an element in the solid state is approximately 6·4. This is true for a large number of elements. Hence an approximate value of the atomic weight is given by the ratio

$$\frac{6{\cdot}4}{\text{specific heat}}$$

The approximate value of the valency is equal to the above approximate atomic weight divided by the equivalent weight, and the actual value of the valency is the integer nearest to this value.

(2) The smallest weight of the element which occurs in a molecule of any of its compounds is probably equal to its atomic weight. Thus, if the molecular weights (cf. p. 8)

of a large number of compounds of the element are known, the atomic weight of the element can be calculated as in the following manner. Taking carbon as an example—

| Compound | Molecular Weight (M) | Parts of Carbon in M Parts of Compound |
|---|---|---|
| Carbon monoxide | 28·0 | 12·0 |
| Carbon dioxide | 44·0 | 12·0 |
| Methane | 16·0 | 12·0 |
| Chloroform | 119 5 | 12 0 |
| Ethane | 30 0 | 24·0 |
| Acetylene | 26·0 | 24·0 |
| Benzene | 78·0 | 72 0 |

Thus the smallest weight of carbon in the molecules of the above compounds is 12·0, and this probably corresponds to the weight of the carbon atom.

(3) *Mitscherlich* concluded that two compounds which formed isomorphous crystals (p. 75) contained in their molecules equal numbers of analogous atoms. He applied this principle to obtain the atomic weights of some elements. For example, potassium sulphate and potassium selenate are isomorphous ($K_2SO_4$; $K_2SeO_4$), and hence in these compounds the valency of the sulphur and the selenium must be the same since the molecules contain equal numbers of analogous atoms. As the valency of sulphur was known previously, this observation enabled the atomic weight of selenium to be calculated.

## AVOGADRO'S HYPOTHESIS

*Gay Lussac* investigated the volumes in which gases react, and concluded that *when gases react together or are formed as the result of a chemical reaction, the volumes reacting or liberated are in a simple ratio to one another* (*Gay Lussac's law*).

This law was explained by *Avogadro* on the hypothesis that *under the same conditions of temperature and pressure, equal volumes of all gases contain the same number of molecules*

(*Avogadro's hypothesis*). This hypothesis leads to the conclusion that the reactions between gases take place between simple numbers of molecules.

For example—

2 volumes of hydrogen combine with 1 volume of oxygen to form 2 volumes of steam.

Therefore

$2n$ molecules of hydrogen combine with $n$ molecules of oxygen to form $2n$ molecules of water.
i.e. 2 molecules of hydrogen combine with 1 molecule of oxygen to form 2 molecules of water.

For some years, Dalton's atomic theory and Avogadro's hypothesis seemed to lead to divergent results, as the distinction between the atom and the molecule of an element was not realized. Although the atom is the smallest particle which takes part in chemical reactions, the atoms of many elements do not exist as individuals in the free state, but combine together to form a molecule of the substance containing two or more atoms. *The molecule of an element or a compound* may be defined as *the smallest portion of the substance capable of independent existence. The molecular weight of the substance* is defined as *the weight of one molecule of the substance relative to one-sixteenth the weight of the atom of oxygen.*

The number of atoms in the molecule of various substances can be deduced by applying Avogadro's hypothesis to the observed gaseous combining volumes, e.g.—

1 volume of hydrogen combines with 1 volume of chlorine to form 2 volumes of hydrogen chloride.

Therefore

1 molecule of hydrogen combines with 1 molecule of chlorine to form 2 molecules of hydrogen chloride.

Each molecule of hydrogen chloride must contain at least one atom of hydrogen and one of chlorine. If it contained more than one atom of each, either the hydrogen or the chlorine could be replaced in more than one stage. As this cannot be effected, it is concluded that only one atom of each element is present in the hydrogen chloride molecule. Therefore the molecule of hydrogen and the molecule of chlorine each contain two atoms—

$$\begin{array}{ccccc} H_2 & + & Cl_2 & = & 2HCl \\ 1\text{ vol.} & + & 1\text{ vol.} & = & 2\text{ vol.} \end{array}$$

The number of atoms in the molecules of other substances may be determined by finding the molecular weight (cf. p. 14), or for simple gaseous substances by measuring the ratio of the specific heat of the gaseous substance at constant pressure to the specific heat at constant volume ($C_p/C_v$). This ratio has the value 1·66 for monatomic gases (i.e. gases with only one atom in the molecule, e.g. mercury vapour, helium, and the other inert gases), 1·4 for diatomic gases (e.g. hydrogen, nitrogen, oxygen), and lower values for gases with more complex molecules.

## THE PROPERTIES OF GASES

The behaviour of gases in regard to variations in temperature and pressure are summarized in Boyle's and Charles's laws.

BOYLE'S LAW states that *at constant temperature, the volume occupied by a gas is inversely proportional to the pressure it exerts.*

CHARLES'S LAW states that *at constant pressure, the volume of a gas increases proportionately to the increase in temperature.*

*The absolute scale of temperature* takes as its zero point that temperature at which the volume of the gas would be reduced to zero if it continued to obey Charles's law. Accordingly this law may be stated in the form: *the volume of a gas is directly proportional to its absolute temperature.*

Boyle's and Charles's laws may be written symbolically thus—

$$\begin{array}{llll} \text{Boyle's law} & P \propto 1/V & \text{i.e. } PV & = \text{constant} \\ \text{Charles's law} & V \propto T & \text{i.e. } V/T & = \text{constant} \end{array}$$

where P, V, and T are the pressure, volume, and absolute temperature of the gas respectively.

By combining the two laws, the following gas equation is obtained.

$$PV/T = \text{constant}$$

and representing the gas constant per gramme-molecule of a gas by the symbol R, the equation becomes

$$PV = RT$$

It follows from Avogadro's hypothesis that the value of the constant R is the same for all gases, for at a given pressure and temperature, 1 gramme-molecule of all gases occupies the same volume. At 0°C and 760 mm (normal temperature and pressure, N.T.P.) this volume is 22·32 l.

The gas equations summarized in the expression

$$PV = RT$$

are not obeyed completely, for as the temperature approaches the point of liquefaction, all gases depart from it to a greater or lesser extent. The theoretically ideal gas which obeys the expression completely is called a *perfect gas.* At ordinary temperatures, the departures from the perfect gas laws are very small for gases such as hydrogen, oxygen, and nitrogen, which are only liquefied at very low temperatures.

DALTON'S LAW OF PARTIAL PRESSURES. *In a mixture of gases, which do not react with one another, each gas exerts the same pressure as if it alone occupied the entire vessel containing the mixture of gases. The total pressure is equal to the sum of the partial pressures due to each gas.* In accordance with this law, when a gas has been collected over water, its partial pressure is equal to the total observed pressure less the tension of aqueous vapour at the temperature of measurement. When correcting the volume of the gas to normal temperature and pressure by applying Boyle's and Charles's laws, the observed pressure must be corrected for the presence of the water vapour.

## THE KINETIC THEORY OF GASES

The laws representing the observed behaviour of gases can be interpreted accurately by the kinetic theory of gases. In accordance with this theory, the large number of molecules present in any gas are quite free and independent of one another, and are moving about at all speeds and in every direction. The moving molecules are continually colliding with one another and with the walls of the vessel containing the gas. The collisions are perfectly elastic, i.e. there is no loss of kinetic energy as the result of collisions.

The pressure exerted by the gas arises from the continuous series of impacts of the moving molecules on the walls of the vessel. It is possible to calculate the magnitude of the pressure in terms of the number of molecules present and their average velocity. As the temperature of the gas rises, the molecules move faster, so that the pressure increases with rise in temperature. By assuming that the kinetic energy of the molecules is proportional to the absolute temperature of the gas and neglecting the sizes of the molecules, it is possible to deduce theoretically the expression

$$PV = RT$$

It is also possible to deduce theoretically Avogadro's hypothesis and *Graham's law of gaseous diffusion* which states that *the rate of diffusion of a gas is inversely proportional to the square root of the density of the gas.*

The departures of the ordinary gases from the perfect gas state can be explained by modifying the simple kinetic theory to allow for the size of the molecules and for the fact that during collisions the molecules remain together for a short time, and do not separate immediately after impact. The modified gas equation (*Van der Waal's equation*) is of the form

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

where $a$ is the factor correcting for the time lag on collision due to the mutual attractions of the molecules, and $b$ corrects for the size of the molecules.

## The Brownian Motion

The kinetic motion of the molecules of fluids may be demonstrated by the *Brownian Motion* of small particles suspended in the fluid. If a suspension of gamboge or a similar substance in water is examined under the microscope, the small particles are seen to be in constant haphazard motion. This motion is due to the impact of the molecules of the water on the particles. It was first observed in 1827 by a botanist, *Brown.*

## THE LIQUEFACTION OF GASES

Up to the middle of the last century, gases were divided into *permanent gases* and *non-permanent gases*, the latter having been liquefied by the application of high pressures. Later it was realized that there is a *critical temperature* for every gas above which it is impossible to liquefy it, but below which it could be liquefied by pressure. Thus the difference between the permanent and the non-permanent gases was seen to be in their critical temperatures, that for the former being lower than any temperature then attained. The attempts to liquefy further gases thus developed into searches for new methods of lowering temperature. The most effective way of doing this was found to be the sudden expansion of the gas from a high to a low pressure. The fall in temperature occurs as a result of separating the molecules of the gas against their mutual attractions. This requires energy which is obtained by lowering the heat energy content of the gas and thus its temperature. All the known gases have been liquefied using this principle, and the commercial production of liquid air is now an important industry.

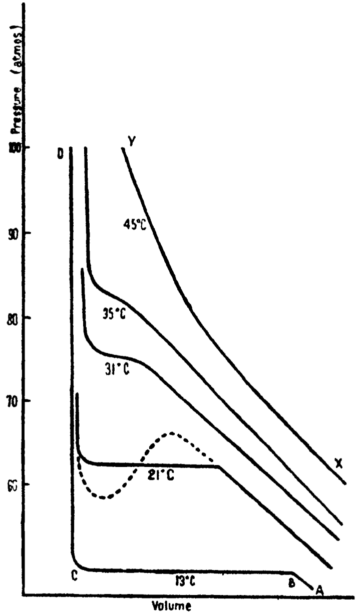

Fig. 1. Isothermals for Carbon Dioxide

The critical phenomena can be illustrated by the curves in Fig. 1, which show the relationship between the pressure and volume of a certain mass of carbon dioxide at different temperatures. At low temperatures an increase in pressure causes a diminution in volume of the gas *AB* until at a certain pressure, *B*, liquefaction occurs; during this process the volume diminishes at constant pressure, i.e. the vapour pressure of the liquid at the particular temperature. After all has been liquefied, $C$, further reduction in volume can only be achieved by pressure increase, $CD$.

At high temperatures, the relation between pressure and volume is given by a smooth curve $XY$, which shows no break because there is no liquefaction. The critical temperature (31°) is revealed clearly by the diagram; above this, liquefaction cannot be produced whatever the pressure. It will be seen that the critical temperature is also associated with a critical pressure and volume (or density).

The dotted curves show the form taken by the theoretical Van der Waal's equation during the zone of liquefaction. The other parts of the curves can be reasonably accurately represented by this equation.

## THE DETERMINATION OF EMPIRICAL FORMULAE

The *empirical formula* of a substance is the simplest formula which represents the *relative* numbers of the atoms of the constituent elements present in the molecules of the compound.

The *molecular formula* of the substance represents the *actual* numbers of atoms of each element present in the molecule of the compound. For example, the empirical formula of glucose is $CH_2O$, its molecular formula being $C_6H_{12}O_6$. In many cases, especially in inorganic chemistry, the molecular formula of a substance is identical with its empirical formula.

| | Carbon | Hydrogen | Oxygen |
|---|---|---|---|
| Relative proportions by weight . . . . | 40·0 | 6·67 | 53·3 |
| Relative weights of the atoms . . . . | 12·0 | 1·008 | 16·0 |
| Hence, relative numbers of atoms . . . . | $\frac{40{\cdot}0}{12{\cdot}0} = 3{\cdot}33$ | $\frac{6{\cdot}67}{1{\cdot}008} = 6{\cdot}66$ | $\frac{53{\cdot}3}{16{\cdot}0} = 3{\cdot}33$ |
| Ratio of numbers of atoms . | 1 | 2 | 1 |

The empirical formula of a substance is calculated from its percentage chemical composition as determined by quantitative chemical analysis (cf. p. 115). For example, a substance was found by chemical analysis to contain 40·0 per cent of carbon, 6·67 per cent of hydrogen, and 53·3 per cent of oxygen. i.e. the empirical formula of the substance is $CH_2O$.

The molecular formula of the substance is obtained from the empirical formula, after the molecular weight of the substance has been determined. For example, if the molecular weight of the above substance was found to be 60, the molecular formula of the substance is $(CH_2O)_2$ since $CH_2O = 30$.

## THE DETERMINATION OF MOLECULAR WEIGHTS

The molecular weight of a substance may be determined by measurements either in the vapour state, or in solution in a suitable solvent.

RELATION BETWEEN VAPOUR DENSITY AND MOLECULAR WEIGHT. The vapour density (V.D.) of the substance is defined in accordance with the relationship

$$\text{V.D.} = \frac{\text{The weight of a certain volume of the vapour of the substance}}{\text{The weight of the same volume of hydrogen at the same temperature and pressure}}$$

Therefore, by Avogadro's hypothesis,

$$\text{V.D.} = \frac{\text{Weight of } n \text{ molecules of the vapour of the substance}}{\text{Weight of } n \text{ molecules of hydrogen}}$$

where $n$ equals the number of molecules in the volume of the gases taken. Since the molecular weight of hydrogen is 2

$$\text{V.D.} = \frac{\text{Weight of 1 molecule of vapour of the substance}}{\text{Weight of 1 molecule of hydrogen}} = \frac{M}{2}$$

*The molecular weight of a substance is equal to twice its vapour density with reference to hydrogen.*

This relationship enables the molecular weight of volatile substances to be determined. The details of the methods used for the determination of vapour density will be found in the textbooks of physical chemistry.

### Osmotic Pressure

The molecular weights of non-volatile substances are found by experiments in solution. The methods are based on observations which are correlated with the phenomena of osmosis and osmotic pressure.

When two solutions of the same substance, but of different concentration, are placed together without mixing, the one diffuses slowly into the other until a uniform composition is attained. If the two solutions are separated by a *semi-permeable membrane* (i.e. a membrane which allows the passage of the solvent, but through which the dissolved substance cannot pass) uniformity is attained by the passage of the solvent through the membrane from the less to the more concentrated solution. This phenomenon is known as *osmosis.* If the diffusion of the solvent is to be prevented, a back pressure must be applied opposing the diffusion.

*The osmotic pressure of a solution is equal to the pressure that is necessary to prevent the solvent diffusing into the solution, when the solution and the pure solvent are separated by a semi-permeable membrane.* The osmotic pressure of a solution is a measure of the tendency of the solvent to diffuse into it through a semi-permeable membrane. In general, diffusion takes place when solutions of different substances in the same solvent are separated by a semi-permeable membrane, but if the two solutions have the same osmotic pressure, no diffusion takes place (*isotonic solutions*).

Many membranes in living cells and organisms are semi-permeable, and osmotic effects are important biologically. When a living cell is placed in an aqueous solution whose osmotic pressure is not the same as that of the cell contents, either water diffuses into the cell and causes its disruption, or the protoplasmic contents of the cell shrink as water diffuses out of it. It is necessary, therefore, that solutions prepared for intravenous injection should be isotonic with normal blood serum.

The osmotic pressure of a solution is measured by the determination of the pressure necessary to prevent the solvent diffusing into it when it is placed on one side, and the pure solvent on the other side of a semi-permeable membrane. The semi-permeable membrane often chosen for quantitative experiments is prepared by depositing copper ferrocyanide in the walls of a porous pot.

It has been found experimentally that, for dilute electrically non-conducting solutions, (1) the osmotic pressure is proportional to the concentration of the solution, (2) the osmotic pressure for a solution of fixed concentration is proportional to the absolute temperature. The observations are combined in the equation

$$\pi V = kT$$

where $\pi$ and V are respectively the osmotic pressure and the volume of the solution containing one gramme-molecule of the dissolved substance. It has been found further that the value of the constant $k$ is independent of the nature of the dissolved substance (provided that the solutions are dilute and electrically non-conducting), and has the same value as the constant R in the gas equation. The equation therefore becomes

$$\pi V = RT$$

It is concluded that the state of the molecules of a substance dissolved in a non-ionizing solvent is comparable with the state of its molecules in the gaseous condition. By applying Avogadro's hypothesis to solutions, it follows that at the same temperature, equal volumes of all dilute non-conducting solutions which exert the same osmotic pressure contain the same number of molecules of the dissolved substance. From this relationship, the concentration of any solution of known osmotic pressure and the relative concentrations of two solutions isotonic with one another may be deduced. For electrically conducting solutions, corrections have to be made for ionization (cf. p. 34).

It can be demonstrated theoretically from the equation

$$\pi V = RT$$

that—

(1) The vapour pressure of a dilute non-conducting solution is lower than the vapour pressure of the pure solvent at the same temperature by an amount proportional to the molecular concentration of the dissolved substance, i.e. the number of gramme-molecules of the substance dissolved in a certain volume of the solvent.

(2) The boiling point of such a solution is higher than that of the pure solvent by an amount proportional to the molecular concentration.

(3) The freezing point of such a solution is lower than that of the solvent by an amount proportional to the molecular concentration. The last two generalizations were first observed experimentally by *Raoult* (1883).

The freezing point and boiling point relationships are often used as the basis of methods of determination of molecular weights. They may be expressed in the form of the equations

$$\Delta_{\mathrm{F.P.}} = k_1\ (x/\mathrm{M})$$
$$\Delta_{\mathrm{B.P.}} = k_2\ (x/\mathrm{M})$$

where $\Delta_{\mathrm{F.P.}}$ and $\Delta_{\mathrm{B.P.}}$ are respectively the lowering of the freezing point and the raising of the boiling point caused by dissolving $x$ g of a substance of molecular weight M in a specified weight of the solvent. $k_1$ and $k_2$ are characteristic constants of each solvent.

By using a substance of known molecular weight, and observing the changes in freezing point or boiling point produced when a weighed quantity is dissolved in a known weight of a solvent, the constants $k_1$ and $k_2$ can be calculated for that solvent. The molecular weight of another substance can then be determined by dissolving a known weight of the substance in the same weight of the solvent, and measuring the alteration produced in the freezing or boiling point.

## THE DETERMINATION OF MOLECULAR VOLUMES

The *molecular volume* of a substance is defined as the volume occupied by 1 gramme-molecular weight of the substance in the liquid form. It is obtained by dividing the molecular weight by the density. It has been found that this is an additive property, i.e. the molecular volume for any substance is equal to the sum of the atomic volumes of the constituent atoms. These atomic volumes have been calculated by comparison of the molecular volumes of many compounds, e.g. atomic volumes for carbon and hydrogen were deduced from a study of the molecular volumes of hydrocarbons thus—

Change in molecular volume from $C_nH_{2n+2}$ to $C_{n+1}H_{2n+4}$ gives the molecular volume of $CH_2$. Twice the volume for hydrogen is obtained by subtracting $nCH_2$ from $C_nH_{2n+2}$, and thus the hydrogen value is obtained. The value for the carbon atom can then be calculated.

When the atomic values have been found, the molecular volumes of all substances can be calculated directly from their formulae, but agreement between theory and experiment is sometimes only approximate.

A similar property called the *parachor* gives rather better agreement between deduced and observed values. The parachor also takes into account the nature of the linkages in the molecular as well as the numbers of the different atoms.

The parachor is essentially a molecular volume measured under conditions of equal liquid surface tensions. It is based on an experimental generalization correlating density and surface tension

$$(D - d) \times C = \gamma^{\frac{1}{4}}$$

where $D$ and $d$ are respectively the densities of the liquid and the gas, $\gamma$ is the surface tension, and $C$ is a constant. The parachor ($P$) is defined from a modification of this equation which ignores $d$ compared with $D$.

$$P = M\gamma^{\frac{1}{4}}/D$$

Some typical parachor values are given below

| | | | |
|---|---|---|---|
| C | 4·8 | Single bond | 0 |
| H | 17·1 | Double bond | 23·2 |
| O | 20·0 | Co-ordinate bond | − 1·6 |
| N | 12·5 | 6-membered ring | 6·1 |
| Cl | 54·3 | | |

# CHAPTER II

## CHEMICAL CHANGE

A CHEMICAL change may be altered by certain factors. In some cases the chemical reaction may be altered in such a way that entirely different products are obtained. For example, the action of ethyl alcohol and sulphuric acid yields ethyl hydrogen sulphate, ether, or ethylene depending on the temperature and the relative proportions of the reacting substances (cf. p. 351).

$$C_2H_5OH + H_2SO_4 = C_2H_5HSO_4 + H_2O$$
$$2C_2H_5OH = (C_2H_5)_2O + H_2O$$
$$C_2H_5OH = C_2H_4 + H_2O$$

Similarly the action of dilute sulphuric acid on potassium ferrocyanide differs from the action of concentrated sulphuric acid on that substance (cf. p. 297).

But usually, altering the conditions under which the reaction takes place merely influences the speed of the reaction. The speed at which a chemical reaction takes place is affected by various factors, the most important of which are (1) the concentration of the reacting substances, (2) temperature, (3) pressure in the case of certain gas reactions, (4) in certain cases, the presence of catalysts, (5) in some cases, the condition of the reacting substances, (6) in a small number of cases, light.

### Effect of the Concentration of the Reacting Substances on the Rate of Reaction

For quantitative purposes, the rate of a chemical reaction is defined as the quantity of the reacting substances transformed in unit time.

$$\text{Rate} = \frac{\text{Quantity transformed}}{\text{Time}}$$

But as the rate of any reaction varies from instant to instant, it is necessary to specify the rate at a particular instant. This may be defined as the quantity of reactants which would be transformed in unit time if the rate of the reaction continued constant at its value for the particular instant.

The rate of change is represented accurately in the language of the differential calculus

$$\text{Rate} = dx/dt$$

where $dx$ represents the quantity of the reactants transformed during an infinitesimally small interval of time $dt$ at the particular instant.

## The Law of Mass Action

In the gaseous or liquid states, the molecules are in continuous motion, and a chemical reaction between two substances is conditioned by the chance that two reacting molecules may collide with one another as the result of their kinetic motion. The chance of collision is proportional to the number of each of the reacting molecules present in unit volume. Thus the rate at which two substances react together is proportional to their respective concentrations, as represented by the equations

Reaction $A + B \rightarrow \ldots$ Rate of reaction $\propto [A] \times [B]$

Reaction $2A \rightarrow \ldots$ Rate of reaction $\propto [A] \times [A]$ i.e. $\propto [A]^2$

where the symbols written with the square brackets are taken to represent the concentration of the various reacting species concerned. *The law of mass action* states that *the rate of a chemical reaction is directly proportional to the product of the active masses of the reacting substances*, where the term *active mass* represents the number of molecules or equivalents of the substance in unit volume. For reactions in solution, the active mass is measured by the number of gramme-molecular weights or gramme-equivalent weights of the substance per litre. For reactions in the gaseous state, the active masses of the reactants are proportional to their partial pressures.

A reaction of the type

$$A \rightarrow B + C$$

in which single molecules of the reacting substance are concerned is called a *unimolecular reaction* or *reaction of the first order*. The rate of the reaction is given by the expression

$$\text{Rate} \propto [A]$$

The inversion of sucrose in the presence of acid catalysts

(p. 462) is an example of this type of reaction. At any instant, the rate of conversion of the sucrose is proportional to the quantity of unchanged sucrose present.

Reactions of the type

$$A + B \rightarrow C + D$$

or

$$2A \rightarrow B + C$$

are called *bimolecular reactions* or *reactions of the second order.* Most chemical reactions are of this type, and although termolecular and higher order reactions are found, they are not common, as reactions involving a large number of molecules usually proceed as a series of *consecutive reactions.* This may occur even with apparently simple reactions, e.g. the reaction

$$CH_3.CO.CH_3 + Br_2 = CH_3.CO.CH_2Br + HBr$$

proceeds in stages according to the equations

$$CH_3.CO.CH_3 \rightarrow CH_3.C(OH){=}CH_2$$

$$CH_3.C(OH){=}CH_2 + Br_2 \rightarrow CH_3.C(OH)Br.CH_2Br$$

$$CH_3.C(OH)Br.CH_2Br \rightarrow CH_3.CO.CH_2Br + HBr.$$

## Influence of Temperature on Reaction Rate

The rate of most chemical reactions increases rapidly with rise in temperature. On the average, a rise of 10°C roughly doubles the rate of reaction. This may be explained in terms of the kinetic theory.

In general, not every collision between two reacting molecules results in chemical reaction. Reaction only ensues when collisions occur between molecules with sufficiently high kinetic energy. The proportion of such collisions increases rapidly with rise in temperature, and this accounts for the large effect of temperature on most reaction rates.

## Effect of Pressure on Reaction Rate

Pressure has no appreciable effect on reactions between solids and liquids, but increase of pressure usually increases the rate of reactions between gases.

## Effect of Catalysts on Reaction Rate

The rate of a chemical reaction is often profoundly influenced by the presence of small quantities of other substances (*catalysts*). In some cases, the reaction is proceeding so slowly in the absence of the catalyst, that the addition of the catalyst seems to start the reaction. Catalysts are themselves unaltered as the result of the chemical reactions whose rate they influence, so that a very small quantity of the catalyst is capable of affecting the reactions between large quantities of the reacting substances.

Usually, catalysts increase the rate of the chemical reaction (*positive catalysis*), but in some cases the reaction rate is slower in the presence of a small quantity of the other substance (*negative catalysis* or *inhibition*). As an example of positive catalysis, the use of platinum in the contact process for the manufacture of sulphuric acid (p. 177) may be mentioned. The addition of acetanilide and phosphoric acid as preservatives to hydrogen peroxide (p. 150) is an example of inhibitor action.

Catalysts are often very specific in their action, i.e. a particular catalyst often is effective for one reaction or one type of reaction only. For reactions involving hydrogenation nickel is a very good catalyst (p. 331), while platinum is effective for reactions involving oxidation (pp. 177, 189). Enzymes (p. 356) are often highly specific in their catalytic effects.

In some cases, the products formed by a chemical reaction catalyze the reaction, which therefore proceeds at an ever increasing rate. This effect is called *autocatalysis*.

### THE MECHANISM OF CATALYSIS

Catalytic reactions are of two types: (*a*) *homogeneous catalysis*, in which all the substances taking part in the reaction (including the catalyst) are in the same state or phase, i.e. all gaseous, or all dissolved in the same liquid; (*b*) *heterogeneous catalysis*, in which the catalyst is not in the same phase as the reacting substances. In these cases, the catalyst is usually a solid.

The mechanism of catalysis is usually explained either in terms of the formation of an intermediate compound, or (as for most cases of heterogeneous catalysis) in terms of adsorption (p. 91).

*The intermediate compound theory* postulates that one or both reactants form a compound with the catalyst, and this intermediate compound reacts to form the final products. The action of iodine as a catalyst for the chlorination of aromatic hydrocarbons (p. 490) may be explained in terms of this theory, in accordance with the following equations which indicate that iodine monochloride is the true chlorine carrier.

$$I_2 + 3Cl_2 = 2ICl_3$$
$$C_6H_6 + ICl_3 = C_6H_5Cl + ICl + HCl$$
$$ICl + Cl_2 = ICl_3$$

An intermediate compound ($C_6H_6$, $2AlCl_3$) has also been isolated in the *Friedel and Craft's* reaction in which aluminium chloride is used as the catalyst (cf. p. 492).

*The adsorption theory* explains heterogeneous catalytic activity in terms of the enhanced reactivity caused by the adsorption of at least one of the reactants on to the surface of the solid catalyst. The catalytic activity in these cases depends on the state of the catalyst surface, and may be seriously diminished by poisoning (p. 91). The contact process reactions (p. 177), the synthesis of ammonia (p. 186), the oxidation of ammonia (p. 189), and the hydrogenation of unsaturated compounds (p. 331) are catalytic reactions of this type.

## Influence of Condition of Reacting Substances on Reaction Rate

It is not possible to give a general statement of the effects of the condition of the reacting substances on the reaction rate. Solid substances usually react at greater speed when finely divided. The solvent often influences the rate of chemical reactions in solution.

The difference in reactivity of ordinary hydrogen and freshly generated hydrogen (cf. p. 146) may also be mentioned in this connexion.

## Influence of Light on Chemical Reaction

Light is a form of energy, and when light is absorbed chemical change may take place by reason of the gain in energy. Reactions brought about by light are called *photochemical reactions*. In general, light of the shorter wave-lengths of the visible spectrum (i.e. blue and violet light) and ultraviolet light are the most active photochemically. The following reactions are brought about by the absorption of light: the decomposition of silver halides (p. 271), the reaction of hydrogen and chlorine (p. 155), the conversion of fumaric acid to maleic acid (p. 413), the chlorination of aromatic hydrocarbons (p 489), the conversion of ergosterol to vitamin D, and the formation of the coloured compound used as the basis of the official assay of Ergot (p. 581).

## CHEMICAL EQUILIBRIUM

Many chemical reactions are reversible, and proceed in either direction. For example, ethyl alcohol reacts with acetic acid to form ethyl acetate and water, while ethyl acetate and water react to form ethyl alcohol and acetic acid (p. 350). Symbolically, the reaction is represented as

$$\underset{\text{Acetic Acid}}{CH_3.COOH} + \underset{\text{Ethyl Alcohol}}{C_2H_5OH} \rightleftharpoons \underset{\text{Ethyl Acetate}}{CH_3.COOC_2H_5} + H_2O$$

By varying the conditions, one reaction or the other can be made to predominate, but usually, in cases of this kind, the two reactions proceed simultaneously. In a mixture of ethyl alcohol, acetic acid, ethyl acetate, and water, reactions to form and to hydrolyze the ethyl acetate proceed at the same time. These reactions oppose one another, and under certain conditions, the rate of formation of ethyl acetate by the one reaction is exactly balanced by its rate of hydrolysis by the other reaction. A state of equilibrium is attained and the composition of the solution remains unaltered.

*Chemical equilibrium* is not a static equilibrium, but a dynamic equilibrium between opposing reactions proceeding at equal rates in opposite directions, so that their effects neutralize one another.

Slow chemical reactions take place whenever mixtures are made of ethyl alcohol and acetic acid, ethyl acetate and water, or any three, or all four of these substances. The composition of the mixture alters as the result of these reactions, until the equilibrium state is reached, after which no further change in composition takes place.

The relative proportions of the four substances present in the equilibrium mixture may be deduced by applying the law of mass action as follows—

Rate of formation of ethyl acetate (forward reaction)

$$= k_1[C_2H_5OH][CH_3.COOH]$$

Rate of hydrolysis of ethyl acetate (back reaction)

$$= k_2[CH_3.COOC_2H_5][H_2O]$$

For equilibrium, the rates of formation and hydrolysis are equal, i.e.

$$k_1[C_2H_5OH][CH_3.COOH] = k_2[CH_3.COOC_2H_5][H_2O]$$

or

$$\frac{[C_2H_5OH][CH_3.COOH]}{[CH_3.COOC_2H_5][H_2O]} = \frac{k_2}{k_1} = K$$

where K is the *equilibrium constant* of the reaction. When the value of K has been determined, it is possible to calculate the composition of the equilibrium mixture reached when different proportions of the reactants are present initially.

The following deductions may be made from the equilibrium equation—

(1) If a product of one reaction is continuously removed from the reaction mixture, that reaction will proceed to completion, e.g. ethyl acetate is completely hydrolyzed in alkaline solution owing to the removal of the acetic acid by conversion into its salt.

$$CH_3.COOC_2H_5 + NaOH = CH_3.COONa + C_2H_5OH$$

(2) The addition of a large excess of one reagent shifts the equilibrium. The direction of the shift favours the reaction in which the excess reagent takes part. For example, in presence of a large excess of water, ethyl acetate is almost completely hydrolyzed.

$$CH_3.COOC_2H_5 + H_2O \rightarrow CH_3.COOH + C_2H_5OH$$

These two deductions have many important applications. In the official method of assay, arsenious compounds are titrated with iodine.

$$As_4O_6 + 4I_2 + 10H_2O \rightleftharpoons 4H_3AsO_4 + 8HI$$

The reaction is reversible, and only proceeds to completion if the acid formed during the titration is continuously removed by reaction with sodium bicarbonate.

## Effect of Temperature on Chemical Equilibria

Owing to a change in the magnitude of the equilibrium constant, the composition of a mixture in chemical equilibrium varies with the temperature. Of the two reactions taking part in the equilibrium, one is an endothermic reaction, while the other is an exothermic reaction (p. 28). The shift in the equilibrium caused by *raising* the temperature favours the *endothermic* reaction. When the temperature is *lowered*, the *exothermic* reaction is favoured. For example, in the equilibrium

$$2SO_2 + O_2 \rightleftharpoons 2SO_3(\text{liq.}) + 32{,}160 \text{ cal.}$$

the formation of sulphur trioxide is exothermic, so that the equilibrium concentration of this substance decreases with rise in temperature as shown in the table.

TABLE I

| Temperature (°C) | Equilibrium Proportion of Sulphur Trioxide (per cent) |
|---|---|
| 430 | 99 |
| 550 | 85 |
| 640 | 60 |

Temperature also affects the rate of attainment of equilibrium, which is much more rapid at higher temperatures. In the Haber process for the synthesis of ammonia, although a higher proportion of ammonia is present in the equilibrium mixture at 450°C (0·24 per cent at 1 atmosphere) than at 550°C (0·08 per cent), the much greater speed of reaction at the higher temperature enables a larger quantity of ammonia to be obtained within a reasonable time. There is an optimum temperature for the economic working of this process, for at higher temperatures the proportion of ammonia in the equilibrium mixture diminishes rapidly.

By very rapid cooling of a mixture in equilibrium at a higher temperature to a much lower temperature at which the rate of change is extremely slow, a product which is only formed at very high temperatures can be isolated. This process is described as *freezing the equilibrium.* For example, in the synthesis of nitric oxide, which is an endothermic reaction,

$$N_2 + O_2 \rightleftharpoons 2NO - 2 \times 21{,}600 \text{ cal.}$$

the proportion of nitric oxide in the equilibrium mixture is greater at higher temperatures (½ per cent at 1,500°C, 5 per cent at 3,000°C). In order to obtain a good yield of nitric oxide, it is necessary to heat the gases to a very high temperature (3,000°C). But if the heated gases were then allowed to cool down slowly, the nitric oxide formed would decompose as the equilibrium composition shifted. This is prevented by cooling the gases very rapidly to 1,000°C, below which temperature the rate of decomposition of nitric oxide is negligibly slow.

## Effect of Pressure on Chemical Equilibrium

Chemical equilibria in the gaseous state are affected by pressure when the reaction proceeds with a change in volume. The reaction which is accompanied by a *decrease in volume* is favoured by an *increase in pressure.* Thus in the synthesis of ammonia, the proportion of ammonia in equilibrium with hydrogen and nitrogen is greater at higher pressures.

$$\begin{array}{ccccc} N_2 & + & 3H_2 & \rightleftharpoons & 2NH_3 \\ 1 \text{ vol} & & 3 \text{ vol} & & 2 \text{ vol} \end{array}$$

$$4 \text{ vol} \rightarrow 2 \text{ vol}$$

This is shown in the following table—

TABLE II

| Temperature (°C) | Pressure (Atmospheres) | Equilibrium Proportion of Ammonia (per cent) |
|---|---|---|
| 500 | 1 | 0·1 |
| ,, | 50 | 5·7 |
| ,, | 100 | 10·4 |
| ,, | 200 | 17·6 |

Pressure does not affect the equilibrium when no change in volume occurs during the reactions as in the equilibrium

$$\begin{array}{ccc} H_2 + & I_2 \rightleftharpoons & 2HI \\ 1\ \text{vol} & 1\ \text{vol} & 2\ \text{vol} \end{array}$$

$$2\ \text{vol} \rightarrow 2\ \text{vol}.$$

The effects of temperature and pressure on chemical equilibria have many important applications. They may be summarized in the generalization known as *Le Chatelier's principle* which states that *when the external conditions applied to systems in chemical equilibrium are altered, the equilibrium is shifted in a direction opposing the change in the conditions.*

## Effect of Catalysts on Chemical Equilibria

The speed of attainment of chemical equilibrium is often influenced profoundly by the presence of catalysts. In reversible reactions the catalyst modifies the speed of both reactions to an equal extent. Consequently, the final composition of the equilibrium mixture is not altered by the presence of the catalyst.

## HEAT OF REACTION

Chemical reactions are usually accompanied by an evolution or an absorption of heat. An *endothermic reaction* is one which is accompanied by an absorption of heat, while an *exothermic reaction* is one which is accompanied by an evolution of heat.

The *heat of a reaction* is defined as the heat (measured in calories*) evolved when the weights, in grammes (as indicated by the equation stated) of the substances concerned, react together. Endothermic reactions have a negative value for the heat of reaction.

*The law of conservation of energy*, which states that *the total energy of any isolated system is constant*, leads to the conclusion that the total amount of heat liberated or absorbed when passing from one set of conditions to another is independent of the processes by which the total change is effected. Thus *the amount of heat evolved or absorbed in any chemical change is the same, independently of the intermediate reactions used to bring about the change* (*Hess's law*).

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* The kilogramme calorie which equals 1,000 calories, is sometimes used to express heats of reaction. It is represented by the symbol Cal.

For example, the heat of combustion of carbon to form carbon dioxide is the same whether the reaction is carried out in one or two stages.

$$\begin{aligned} C + \tfrac{1}{2}O_2 &= CO + 29{,}000 \text{ cal} \\ CO + \tfrac{1}{2}O_2 &= CO_2 + 67{,}960 \text{ ,,} \\ C + O_2 &= CO_2 + 96{,}960 \text{ ,,} \end{aligned}$$

The heat of a reaction varies with the physical conditions of the reactants and the products, and with the temperature. The variations can be calculated from the specific heats and latent heats of the substances concerned.

For example,

$$H_2 + \tfrac{1}{2}O_2 = H_2O \text{ (liquid)} + 68{,}360 \text{ cal at } 15^\circ \text{ C.}$$

The heat of the reaction

$$H_2 + \tfrac{1}{2}O_2 = H_2O \text{ (steam) at } 100^\circ \text{ C.}$$

is equal to $68{,}360 - S_1 \quad L + S_2$

where $S_1$ and $S_2$ represent the amount of heat required to raise the temperature of the reacting weights of the water and the mixed gases respectively from 15° C to 100° C, and L is the latent heat absorbed when 18 g of water are converted into steam. Using the experimental figures, the heat of reaction at 100° C becomes

$$68{,}360 - (18 \times 85) - (537 \times 18) + 892 \text{ cal} = 58{,}056 \text{ cal.}$$

The *heat of formation of a substance* is defined as the heat evolved during the formation of 1 gramme-molecular weight of the substance from its constituent elements. A substance which has a positive value for the heat of formation is said to be an *exothermic compound*, while a substance which has a negative value for the heat of formation is said to be an *endothermic compound*.

Heats of formation are usually calculated from observed heats of reaction. Conversely, if the heats of formation of all the substances taking part in a reaction are known, the heat of the reaction can be calculated.

The heat of formation of methane can be calculated from the heats of the following reactions thus—

$$\begin{aligned} CH_4 + 2O_2 &= CO_2 + 2H_2O \text{ (liq.)} + 212{,}400 \text{ cal} \\ C + O_2 &= CO_2 \qquad\qquad\qquad + 96{,}960 \text{ ,,} \\ H_2 + \tfrac{1}{2}O_2 &= H_2O \text{ (liq.)} \qquad\quad + 68{,}360 \text{ ,,} \end{aligned}$$

Hence

$$\begin{aligned} C + 2H_2 &= CH_4 + 212{,}400 - 96{,}960 - 2 \times 68{,}360 \\ &= 21{,}280 \text{ cal.} \end{aligned}$$

The solution of most substances in solvents is accompanied by the evolution or absorption of heat. This is due to the energy changes involved in (1) the separation of the substance into isolated, freely-moving molecules; (2) ionization; (3) solvation (p. 148). The heat evolved or absorbed depends on the quantities of the substance and solvent used.

## CHAPTER III

## ELECTROLYTIC CONDUCTION AND THE IONIC THEORY

SOLUTIONS of acids, bases, and salts in water, and many fused salts are conductors of electricity. The electrical conduction of such substances differs from the conduction of metals, for the passage of the electric current through these solutions and fused salts brings about chemical changes.

In order to make contact with the rest of the electrical circuit, two pieces of a non-reacting metal (e.g. platinum), or other conducting substance (e.g. graphite), must be placed in the solution, and the products of chemical change brought about by the current appear at these pieces of metal, or *electrodes*. For example, when a current is passed through dilute sulphuric acid solution, hydrogen is evolved at one electrode, and oxygen is evolved at the other.

The electrode connected to the positive pole of the electric battery is called the *anode*, while the electrode connected to the negative pole is the *cathode*. Substances which conduct electricity with the accompaniment of chemical change are called *electrolytes*, the process being known as *electrolysis*. When dilute sulphuric acid is electrolyzed, hydrogen and oxygen appear at the cathode and anode respectively.

### Faraday's Laws of Electrolysis

Faraday investigated the phenomena of electrolytic conduction, and concluded that—

(1) The amount of chemical decomposition is proportional to the current and the time for which it is passed through the solution, i.e. proportional to the quantity of electricity passed through the solution.

(2) If the same quantity of electricity is passed through a series of solutions, the amount of any substance or radical liberated is proportional to its chemical equivalent.

The second law may be expressed in the following form: the chemical equivalent of any element or radical requires for its liberation the same quantity of electricity. This quantity of electricity (96,540 coulombs) is sometimes called the *Faraday*.

In order to interpret these observations, it was suggested that electrolytes contain electrically charged particles, which are called *ions*. Since the solution is electrically neutral as a whole, equal numbers of positively and negatively charged ions are present. When the electric current is passed through the solution, the positively charged ions become attracted and migrate to the negative electrode (cathode), while the negatively charged ions move towards the positive electrode (anode). At the electrodes the charges on the ions are neutralized, and the uncharged radicals are liberated. The metallic radicals of the simple salts and the hydrogen of acids are always liberated at the cathode, so that these radicals and atoms must form the positively charged ions (or *cations*). Acid radicals are liberated at the anode, and thus form the negatively charged ions (or *anions*). In size, ions correspond to single metal atoms and the corresponding metallic or acidic radicals carrying the appropriate charge.

It follows, from Faraday's second law, that every ion has a certain definite charge proportional to its valency. It is found that every univalent anion carries a negative charge equal to that of the electron (cf. p. 304), while every univalent cation carries a positive charge of the same magnitude. The charges on bivalent and tervalent radicals are two and three times greater than the charge on univalent ions respectively.

$$KCl \rightleftharpoons K^{+} + Cl^{-}$$
$$BaCl_2 \rightleftharpoons Ba^{++} + 2Cl^{-}.$$

These postulates enable the results obtained when various solutions are electrolyzed to be interpreted.

*Electrolysis of dilute sulphuric acid*

At cathode $H^{+} \rightarrow H$; $2H = H_2$
At anode $SO_4^{--} \rightarrow SO_4$; $2SO_4 + 2H_2O = 2H_2SO_4 + O_2$
or $OH^{-} \rightarrow OH$; $4OH = 2H_2O + O_2$

*Electrolysis of sodium chloride solution*

(*a*) Products at the electrodes being kept apart
At cathode $Na^{+} \rightarrow Na$; $2Na + 2H_2O = 2NaOH + H$
At anode $Cl^{-} \rightarrow Cl$; $2Cl = Cl_2$

(*b*) Products formed being allowed to mix

Cold solutions $2NaOH + Cl_2 = NaCl + NaClO + H_2O$

Hot solutions $6NaOH + 3Cl_2 = 5NaCl + NaClO_3 + 3H_2O$

*Electrolysis of fused sodium chloride*

At cathode $Na^+ \rightarrow Na$

At anode $Cl^- \rightarrow Cl; \quad Cl + Cl = Cl_2$

*Electrolysis of copper sulphate solution between copper electrodes*

At cathode $Cu^{++} \rightarrow Cu$. Copper deposited.

At anode $SO_4^{--} \rightarrow SO_4; \quad Cu + SO_4 = CuSO_4$. Copper dissolved.

From the above examples, it is clear that the products obtained by the electrolysis of a solution may not arise directly, but are sometimes produced by secondary reactions which occur at the electrodes.

*Electrolytic reduction.* Electrolytic changes in which hydrogen is produced at the cathode can be applied to bring about reduction if other substances are added to the electrolyte, e.g. acetone may be reduced to isopropyl alcohol (cf. p. 380) if it is added to a dilute sulphuric acid solution which is being electrolyzed. Nitrobenzene can be reduced electrolytically to a number of products (cf. p. 496).

The efficiency of the reduction is altered by varying (1) the voltage, (2) the current density, i.e. the magnitude of the electric current used divided by the surface area of the cathode, (3) temperature, (4) concentration of the solution, (5) nature of the electrodes.

*Electrolytic oxidation.* Substances may be oxidized electrolytically if present in a solution when oxygen or some other oxidizing substance (e.g. chlorine) is being liberated at the anode. The efficiency of the oxidation process is controlled by similar factors to those controlling the reduction process. The following are examples of electrolytic oxidation reactions; the preparation of sodium hypochlorite and chlorate (pp. 158, 160) and the preparation of persulphates (p. 181).

*Polarization.* Very often in electrolysis the accumulation of the products of chemical change at the electrodes alters the electrode potentials. Thus, when an acid is electrolyzed, the accumulation of hydrogen at the cathode impedes the continuance of the electrolysis and may stop the passage of the current altogether. The electrode is said to have been polarized and the back e.m.f. resulting from the polarization, which tends to stop electrolysis proceeding, is called the *polarization electromotive force*. Polarization due to hydrogen formation can often be prevented or obviated by carrying out the electrolysis in the presence of an oxidizing agent. Thus manganese dioxide is used as a depolarizer in the manufacture of dry batteries.

Most of the reactions of inorganic chemistry which take place in aqueous solution are ionic in character. For this reason, the ordinary analytical reactions of the metals and acid radical are given independently of the state of combination of the atom or radical. Thus all silver salts give a precipitate of silver chloride with all soluble chlorides, for the reaction takes place between the silver ion and the chloride ion.

$$Ag^+ + Cl^- = AgCl$$

(Silver salts do not react to precipitate silver chloride from compounds in which the chlorine is combined in a non-ionizable form, e.g. chloroform.)

Further, it is not possible to distinguish qualitatively between salt mixtures in solution, e.g. a solution prepared by dissolving potassium nitrate and sodium chloride in water is indistinguishable from a solution prepared from sodium nitrate and potassium chloride. The ionic theory also explains why solutions of all permanganates have the same colour, for the colour is due to the permanganate ion.

Ionic reactions proceed so rapidly as to be practically instantaneous. The actual observed reaction rates are controlled by other velocities such as the rate of mixing the solutions, which are much slower than the combination between the reacting ions.

## Degree of Ionization

*Arrhenius* was the first worker to calculate the extent to which acids, bases, and salts were reversibly ionized in solution. It was known that the substances which formed electrically conducting solutions gave inexplicably low values for their molecular weights when examined by the ordinary methods for the determination of the molecular weights of dissolved substances (p. 17). For example, the molecular weight of sodium chloride when dissolved in water is not much more than half the expected molecular weight, and the molecular weight of barium chloride in solution is about one-third the expected value. Arrhenius calculated the degree of ionization of these substances assuming that the low values of the molecular weights were caused by the ionization.

If sodium chloride (molecular weight 58·5) were completely dissociated into sodium and chloride ions (weights 23·0 and 35·5 respectively) the apparent molecular weight would be 29·25, i.e. half the real value. Similarly if barium chloride were completely dissociated, three ions would be formed from every dissolved molecule, so that its apparent molecular weight would be one-third the expected value.

$$BaCl_2 \rightarrow Ba^{++} + 2Cl^-$$

Arrhenius concluded that the experimental values are not quite one-half or one-third the expected values because ionization is not quite complete, and he calculated from the experimental values the exact proportions of the substances dissociated into ions in solutions of various concentrations.

During his studies on osmotic pressure, *Van't Hoff* had deduced that substances which form electrically conducting solutions obeyed the osmotic pressure relationship

$$\pi V = iRT$$

where $i$ represents the departure from the equation $\pi V = RT$ which is obeyed for non-electrolytes.

$i$ is called *Van't Hoff's coefficient* (sometimes the *isotonic coefficient*). It may be defined by the expression

$$i = \frac{\text{observed osmotic pressure}}{\text{theoretical osmotic pressure assuming substance has normal molecular weight}}$$

In this equation, the freezing point depressions, lowerings of vapour pressure, or elevations of boiling point may be substituted for the osmotic pressures.

Arrhenius showed that the value of $i$ is determined by the ionization of the substance Thus for a substance which dissociates into two ions only (e.g. sodium chloride), if the fraction dissociated in a certain solution is $\alpha$, then the fraction undissociated is $1 - \alpha$.

$$\underset{1-\alpha}{NaCl} \rightleftharpoons \underset{\alpha}{Na^+} + \underset{\alpha}{Cl^-}$$

The total number of particles present in the solution is

$$1 - \alpha + 2\alpha = 1 + \alpha$$

times the number of molecules of sodium chloride dissolved. Hence

$$i = 1 + \alpha$$

In a similar manner, it can be shown that for a substance which dissociates to form $n$ ions,

$$i = 1 + (n - 1)\alpha$$

i.e. $$\alpha = (i - 1)/(n - 1)$$

The degree of ionization of electrolytes can therefore be calculated from the value of the Van't Hoff coefficient.

Arrhenius found also that the degree of ionization could be calculated from the observed electrical conductivity of the solutions. The values obtained by this method agree well with the values obtained from molecular weight determinations. The degree of ionization of some substances is shown in the table.

TABLE III

| Substance | Degree of Dissociation ($\alpha$) in N/10 Solution |
|---|---|
| *Acids*— | |
| Nitric acid | 0·92 |
| Hydrochloric acid | 0·92 |
| Sulphuric acid | 0·60 |
| Acetic acid | 0·01 |
| Carbonic acid | 0·0017 |
| Boric acid | 0·0001 |
| *Alkalis*— | |
| Potassium hydroxide | 0·93 |
| Sodium hydroxide | 0·88 |
| Ammonia | 0·01 |
| *Salts*— | |
| Potassium chloride | 0·86 |
| Sodium chloride | 0·85 |
| Sodium nitrate | 0·82 |
| Potassium sulphate | 0·72 |
| Sodium acetate | 0·79 |
| Ammonium chloride | 0·84 |

The table shows that substances vary widely in the extent to which they ionize in aqueous solution. Many acids and bases, and most salts are almost completely ionized even at fairly high concentrations. These are called the *strong electrolytes*. Other acids and bases are only dissociated to a slight extent, and these are the *weak electrolytes*. A few substances are intermediate in character.

The *strength of an acid or base* depends on its degree of dissociation, the strongest being the most dissociated.

With all ionizing substances, it is found that the degree of dissociation increases with dilution. It is probable that even the weakest electrolyte could be shown to be completely ionized in extremely dilute solutions, if measurements could be made with such solutions.

## Variation in Degree of Ionization with Concentration

The reversible dissociation of any electrolyte into ions is determined by the law of mass action. In the case of the equilibrium

$$A^+ + B^- \rightleftharpoons AB$$

the following relationship is obtained

$$\frac{[A^+][B^-]}{[AB]} = \text{constant (K)}.$$

The constant K is called the *electrolytic dissociation constant* of the substance AB. The variation of the degree of dissociation of AB with concentration of its solution can be derived from this equation thus—

Let the fraction of AB that is ionized be $\alpha$, when one gramme-equivalent of AB has been dissolved to give a volume of solution of $v$ litres. A fraction $1 - \alpha$ then remains un-ionized. Under these circumstances, the concentration of each ion is $\alpha/v$ equivalents per litre, while the concentration of the un-ionized salt is $(1 - \alpha)/v$ equivalents per litre.

| | $AB \rightarrow$ | $A^+ +$ | $B^-$ |
|---|---|---|---|
| Fraction | $1 - \alpha$ | $\alpha$ | $\alpha$ |
| Concentration | $(1 - \alpha)/v$ | $\alpha/v$ | $\alpha/v$ |

Substituting in the mass action equation, the following expression is obtained

$$\frac{[A^+][B^-]}{AB} = \frac{\frac{\alpha}{v} \times \frac{\alpha}{v}}{\frac{1-\alpha}{v}} = \frac{\alpha^2}{(1-\alpha)v} = K.$$

This equation, which correlates the degree of dissociation ($\alpha$) of a substance with the dilution of its solution, was first derived by *Ostwald*. It is known as the *Ostwald Dilution Law.* It agrees with the observed behaviour of weak electrolytes, i.e. substances which are not very much dissociated at ordinary dilutions.

Strong electrolytes do not behave in this way, as will be seen from the examples in the following table. It is now realized that these are really completely dissociated at all ordinary concentrations. The apparent incomplete dissociation (as calculated by Arrhenius) is due to the electrical forces operating between the ions when they are present in considerable

TABLE IV

| Volume of Solution ($v$) Containing One Gramme-Molecule (Litres) | Degree of Dissociation $\alpha$ | $\frac{\alpha^2}{(1-\alpha)v} = K$ |
|---|---|---|
| *Acetic acid at 25°C*— | | |
| 13·57 | 0·0157 | 0·00001845 |
| 27·14 | 0·02216 | 0·00001851 |
| 54·28 | 0·03118 | 0·00001849 |
| 108·56 | 0·04380 | 0·00001849 |
| 434·2 | 0·08568 | 0·00001849 |
| 1,737·0 | 0·1641 | 0·00001854 |
| 6,948·0 | 0·3013 | 0·00001870 |
| *Potassium Chloride*— | | |
| 10 | 0·8680 | 0·571 |
| 20 | 0·8968 | 0·390 |
| 50 | 0·9295 | 0·245 |
| 100 | 0·9486 | 0·175 |
| 200 | 0·9638 | 0·128 |
| 500 | 0·9785 | 0·0895 |
| 1,000 | 0·9866 | 0·0726 |

concentrations. These forces tend to draw the ions of opposite sign together, so that the mobility of the ions, and hence the conductivity of the solution, are less than they would be if each ion behaved as a completely independent individual.

The theory of complete ionization is supported by the fact that most crystalline salts are completely ionized in the solid state (cf. p. 313). Consequently, solution merely involves the separation of the ions.

### Relative Speeds of Ions

During electrolysis the various cations and anions do not move with equal speeds, so that concentration changes occur in the neighbourhood of the two electrodes. If the velocities of the cation and anion in a given solution are respectively $u$ and $v$, and if a current is passed through the solution for unit time, all the cations within a distance $u$ of the cathode and all the anions within a distance $v$ of the anode will reach their respective electrodes and be discharged. This is equivalent to the passage of $u$ units of positive electricity in one direction and $v$ units of negative electricity in the opposite direction, i.e. to the total passage of $u + v$ units. Thus we can define two ratios $\left(\frac{u}{u+v} \text{ and } \frac{v}{u+v}\right)$ which are the fractions of the total current which were carried respectively by the cations and the anions. These ratios are called *the transport numbers* of the two ions.

Transport numbers are determined by using an apparatus which enables the solutions in the neighbourhood of the electrodes to be isolated and removed for analysis. These change in composition during electrolysis as the anions move away from the cathode and the cations away from the anode to an extent controlled in each instance by their respective velocities. The changes in composition are thus directly correlated with the transport numbers.

Transport numbers of the various ions are not constant, but vary slightly with total concentration and with temperature.

## ACIDITY, ALKALINITY, AND NEUTRALIZATION IN AQUEOUS SOLUTION

All acids contain hydrogen replaceable by a metal. They are ionized in solution into the hydrogen ion and the acid radical ion, and therefore the only factor common to all acid solutions is the hydrogen ion. *The hydrogen ion is the essential factor for producing acidity.* Similarly, the hydroxyl ion, which is present in all alkaline solutions, is the essential factor for producing alkalinity.

The ordinary equation for the neutralization of an acid by a base is written

$$HX + MOH = MX + H_2O$$

In terms of the ionic theory, the equation is rewritten thus

$$H^+ + X^- + M^+ + OH^- = M^+ + X^- + H_2O$$

i.e. $$H^+ + OH^- = H_2O$$

Thus, *neutralization* takes place when hydrogen ions and hydroxyl ions combine with one another, so that they are both removed from solution in the form of un-ionized water. This process is independent of the nature of the acid and the base neutralizing one another, provided both are strong electrolytes. This may be tested by measuring the heat evolved during the neutralization of different strong acids by different strong bases. It is found by experiment that the heat evolved is practically independent of the nature of the acid or the base.

## The Ionization of Water

It may be proved in several ways, e.g. by the electrical conductivity of pure water, that the combination of hydrogen and hydroxyl ions is really reversible. Thus an equilibrium is set up determined by the law of mass action

$$H^+ + OH^- \rightleftharpoons H_2O$$

$$\frac{[H^+][OH^-]}{[H_2O]} = \text{constant.}$$

As the un-ionized water is present in comparatively large proportion, any variation in its concentration is negligibly small, so that its concentration may be taken as constant. The above equation then becomes

$$[H^+] \times [OH^-] = \text{constant } (K_w).$$

Thus, *all aqueous solutions contain both hydrogen and hydroxyl* *ions*, and *the product of the concentrations of the two ions is constant*. The value of the constant $K_w$ may be calculated from conductivity and other measurements. It varies slightly with temperature, but at ordinary laboratory temperatures the value is very nearly $1{\cdot}0 \times 10^{-14}$, i.e. at these temperatures the concentrations of the hydrogen and hydroxyl ions in pure water are $1{\cdot}0 \times 10^{-7}$ gramme-equivalents per litre.

A *neutral* solution may accordingly be defined as one in which the concentration of hydrogen ions (in gramme-equivalents per litre) is equal to the concentration of the hydroxyl ions (in gramme-equivalents per litre). In such a solution, the concentration of the two ions is $10^{-7}$ gramme-equivalents per litre.

An *acid* solution is one in which the hydrogen ion concentration is greater than the hydroxyl ion concentration, i.e. the hydrogen ion concentration is greater than $10^{-7}$ gramme-equivalents per litre. Conversely, an *alkaline* solution is one in which the hydroxyl ion concentration is greater than the hydrogen ion concentration, i.e. the hydrogen ion concentration is less than $10^{-7}$ gramme-equivalents per litre.

The degree of acidity or alkalinity of any solution may be indicated by expressing the actual concentration of hydrogen or hydroxyl ions in it, for the greater the concentration of the hydrogen ion the more acid is the solution, and conversely the greater the concentration of the hydroxyl ion the more alkaline (or less acid) is the solution.

## The pH Scale

The numbers thus necessary to express the ionic concentrations are often inconvenient. The *p*H scale was devised to afford a more convenient representation: it is derived from the actual concentration of the hydrogen ions in the solution, thus—

The hydrogen ion concentration of a solution of $p\text{H} = x$ is $10^{-x}$ gramme-equivalents per litre. *The* pH *of a solution* may therefore be defined as *the common logarithm of the reciprocal of the hydrogen ion concentration in the solution expressed in gramme-equivalents per litre.*

As $K_w = 10^{-14}$, the concentrations of the hydrogen and hydroxyl ions in solutions of various *p*H values can be calculated as shown in the following table, which demonstrates that a change in *p*H value of one unit corresponds to a tenfold change in the ionic concentrations.

Solutions of *p*H 7 have equivalent proportions of hydrogen and hydroxyl ions, i.e. they are neutral. Solutions whose *p*H values are less than seven have hydrogen ion concentrations greater than hydroxyl ion concentrations, so that they are acid. Similarly solutions of *p*H value greater than seven are alkaline. The lower the *p*H value of a solution, the more acid (or less alkaline) is the solution, and correspondingly the greater the *p*H value the more alkaline (or less acid) the solution. The *p*H scale covers the whole range of acid and alkaline solutions, and is therefore a convenient method of indicating the relative degree of acidity and alkalinity of aqueous solutions.

TABLE V

| | *p*H | Hydrogen Ion Concentration<br>Gm.-equivs. per Litre | Hydroxyl Ion Concentration<br>Gm.-equivs. per Litre |
|---|---|---|---|
| Strongly acid | 0 | $10^{0} = 1$ | $10^{-14}$ |
| | 1 | $10^{-1} = 1/10$ | $10^{-13}$ |
| | 1·5 | $10^{-1.5} = \cdot 0316$* | $10^{-12.5}$ |
| | 3 | $10^{-3} = 1/1000$ | $10^{-11}$ |
| Weakly acid | 5 | $10^{-5}$ | $10^{-9}$ |
| NEUTRAL | 7 | $10^{-7}$ | $10^{-7}$ |
| Weakly alkaline | 9 | $10^{-9}$ | $10^{-5}$ |
| | 11 | $10^{-11}$ | $10^{-3} = 1/1000$ |
| Strongly alkaline | 13 | $10^{-13}$ | $10^{-1} = 1/10$ |
| | 14 | $10^{-14}$ | $10^{0} = 1$ |

* Since antilog 0·5 = 3·16.

## The Measurement of pH Values

There are two general methods of determining the hydrogen ion concentration of an aqueous solution: (1) by electrical measurements, (2) by comparison of indicator colours.

### ELECTRICAL METHODS FOR DETERMINATION OF HYDROGEN ION CONCENTRATION

When a zinc rod is immersed in a solution of a zinc salt, the zinc tends to pass into solution as ions, leaving the metal rod electrically charged negatively. The solution of the metal is opposed by the electric potential thus established, owing to the electrical attraction between positive and negative charges. Thus there is eventually set up an equilibrium depending on the concentration of the zinc ions in solution. The equilibrium electrical potential between the metal and the solution is called the *electrode potential.*

$$Zn \rightleftharpoons Zn^{++} + 2(-)$$

With a copper rod immersed in copper sulphate solution, the tendency of the metal to ionize is much less than that of zinc, and some of the copper ions are deposited on the metal before equilibrium is achieved, so that at equilibrium the copper rod is positively charged with respect to the solution.

$$Cu \rightleftharpoons Cu^{++} + 2(-).$$

Thus it will be seen that the magnitude of electrode potentials depends on the ionization tendency of the metal concerned and the concentrations of the solution in which it is placed.

Correspondingly when a piece of spongy platinum is saturated with hydrogen gas and placed in an aqueous solution, the hydrogen in the spongy platinum (which acts as a reservoir of hydrogen) tends to pass into solution as hydrogen ions, leaving the platinum electrically charged negatively.

$$H_2 \rightleftharpoons 2H \rightleftharpoons 2H^+ + 2(-)$$

The ionization of the hydrogen proceeds until the negative charge of the platinum becomes great enough to prevent further passage of the ions into the solution against the electrical attraction between the negatively charged metal and the positive hydrogen ions.

The value of the equilibrium electrical potential of the platinum depends on the hydrogen ion concentration of the solution, for the concentration of the hydrogen ions determines the tendency for the back reaction to take place.

A theoretical relationship can be deduced between the potential of the hydrogen saturated platinum (or *hydrogen electrode*, as it is called) and the hydrogen ion concentration of the solution. Consequently, the experimental measurement of the potential developed when the hydrogen electrode is placed in a solution enables the *p*H value of the solution to be calculated.

In order to complete the electrical circuit when making the experimental measurements, a second electrode of some other type must be placed in the solution in addition to the hydrogen electrode. The potential which is then measured comprises the potentials of both electrodes.

The second electrode should have a constant and known electrode potential. This is attained by using a *standard electrode*, commonly a *calomel electrode* (mercury in contact with mercurous chloride and either a normal or a saturated solution of potassium chloride). While this electrode is used as an experimental standard electrode, the theoretical standard electrode is defined as the *normal hydrogen electrode*, i.e. the potential of an electrode formed between hydrogen at one atmosphere in a solution containing unit concentration of hydrogen ions. This electrode potential is taken as zero at all temperatures, and that of the standard calomel electrode on this scale is + 0·281 V or 0·246 V at 25 C for normal or saturated potassium chloride solutions respectively.

When determining an electrode potential against a standard electrode, it is necessary to ensure that there is no *liquid junction potential* between the solutions comprising the two electrode systems. This is usually effected by interposing a saturated solution of a suitable non-reactive salt (e.g. ammonium nitrate) between the electrode systems, e.g.—

$$\text{Hydrogen} \mid \text{HCl} \mid \text{NH}_4\text{NO}_3 \mid \text{HgCl} \mid \text{Hg}$$

The electrometric method for the determination of hydrogen ion concentration is sometimes used to follow acid-alkali titrations. The *p*H of one of the solutions is measured, a small measured quantity of the other solution is added, and the $p$H of the mixture again measured. Further quantities of the second solution are added, the $p$H of the resulting solution being measured after each addition. The values obtained may be expressed in the form of a *titration curve*, when the end-point can usually be seen by a sharp sudden change in the direction of the plotted curve. Fig. 2 shows typical electrometric titration curves for various acids and sodium hydroxide.

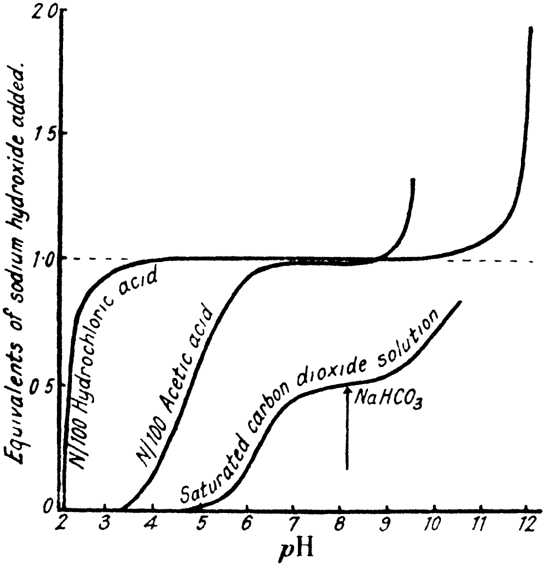


FIG. 2. TITRATION CURVES

The electrical method of determination of hydrogen ion concentration suffers from the disadvantage that the measurements require a special and rather costly apparatus. In some cases also a considerable time is required before the hydrogen electrode reaches its equilibrium value. The indicator methods are more rapid, and do not require elaborate or costly apparatus. They are, however, not quite so accurate as the electrical methods.

## INDICATOR METHODS FOR THE DETERMINATION OF HYDROGEN ION CONCENTRATIONS

The indicator methods for the determination of hydrogen ion concentrations depend on the fact that, in the absence of interfering effects, two solutions which give the same colour with a certain indicator have the same *p*H value. The indicator must be chosen so that the acidity or alkalinity of the solution under examination lies within the range of change of the indicator (cf. p. 49), e.g. the colour of methyl orange changes gradually from red in solutions of *p*H 2·8 to yellow in solutions of *p*H 4·0. Methyl orange can only be used to determine the *p*H of solutions between these values, for two solutions, each more acid than *p*H 2·8 or more alkaline than *p*H 4·0, could not be distinguished from one another by the colour they give with methyl orange.

In order to determine the *p*H of a solution, a series of standard solutions of known *p*H value is made up. The appropriate indicator is added to each of these standards and to the solution under examination. The *p*H of the solution under examination is equal to the *p*H value of that standard solution which gives the same indicator colour.

There are various devices marketed by which the comparison of the standard indicator colours with the colour of the solution under test may be speedily effected. Indicator papers are also available from which the *p*H can be found by matching the colour against a printed series of standards.

Indicator methods cannot be applied in cases where the solution being tested is deeply coloured or contains some substance which precipitates the indicator. Indicator methods do not give very accurate results in the presence of large quantities of neutral salts (e.g. sodium chloride) or proteins. The neutral salt or protein causes the colour of the indicator to correspond with a *p*H value slightly different from that given by a solution of similar composition but without the salt or protein. For example, with phenolphthalein the presence of 6 per cent of sodium chloride causes an apparent alteration in the acidity of a solution by — 0·2 *p*H units.

The causes of the neutral salt error and the protein error are not clear, but *p*H determinations by indicator methods are not infrequently rendered less accurate by them, especially for measurements in biological media.

The solutions of standard *p*H values used in the indicator methods for the determination of hydrogen ion concentrations are made up from formulæ which have been found by electrical measurements to give the required values. A table of such standard solutions is found in the *British Pharmacopœia* (1948), p. 703. As these standards must be reliable, they are made up from buffer solutions.

*Buffer Solutions*

It is not practicable to make up a series of solutions of standard *p*H value by diluting acid or alkaline solutions with pure water (e.g. *p*H 6·0 corresponds roughly to one-millionth normal acid). Such solutions, even if they could be made accurately, would not retain a constant *p*H value very long, for the accidental addition of traces of acid or alkali (e.g. from the carbon dioxide of the air, or alkali from glass) would cause appreciable alterations in this value. The solutions used in the preparation of *p*H standards must be such that accidental additions of small quantities of acid and alkali cause no appreciable alteration in *p*H value. Such solutions are called *buffer solutions.*

Buffer solutions contain a mixture either of a weak acid and its salt (e.g. acetic acid and sodium acetate) or a weak base and its salt (e.g. ammonia and ammonium chloride).

Consider the case of sodium acetate and acetic acid. Like most salts, sodium acetate is almost completely ionized, but only a small fraction of the acetic acid is ionized, the greater part being un-ionized (p. 36).

$$CH_3COOH \rightleftharpoons CH_3.COO^- + H^+$$

Therefore in the mixture of sodium acetate and acetic acid, the proportion of acetate ions is much greater than the proportion of hydrogen ions.

If some free acid is added to the mixture, some of the hydrogen ions combine with some of the excess acetate ions to form undissociated acetic acid. Thus the greater part of the added hydrogen ions are removed and rendered ineffective in altering the *p*H of the solution.

$$CH_3.COO^- + H^+ \rightarrow CH_3.COOH$$

Similarly the solution is not altered appreciably in *p*H value by the addition of alkali, owing to the reserve of undissociated acetic acid, which replaces most of the hydrogen ions removed by combination with the added hydroxyl ions.

$$H^+ + OH^- \rightarrow H_2O$$
$$CH_3.COOH \rightarrow CH_3.COO^- + H^+$$

Buffer solutions are said to have reserve alkalinity and reserve acidity.

Fig. 2 (p. 45) illustrates buffer action, for the neutralization curve of acetic acid with sodium hydroxide is less steep than the corresponding curve for hydrochloric acid.

In symbols, the dependence of the buffer action on the equilibrium

$$CH_3.COOH \rightleftharpoons CH_3.COO^- + H^+$$

is shown by the mass action equation

$$\frac{[CH_3.COO^-]\,[H^+]}{[CH_3.COOH]} = K$$

i.e.
$$[H^+] = \frac{K[CH_3.COOH]}{[CH_3.COO^-]}$$

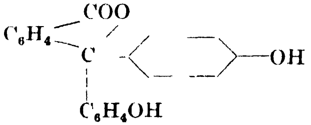
Thus solutions which contain quantities of acetate ions and undissociated acetic acid large enough for alterations in their respective concentration to be comparatively trivial have almost constant *p*H value.

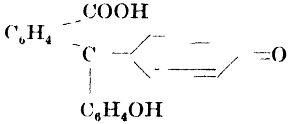
## THE THEORY OF INDICATORS FOR ACID-ALKALI TITRATIONS

An indicator is a complex organic substance which exists in two forms in equilibrium (cf. tautomerism, p. 471). These two forms have different molecular structures, and possess different colours. The one form is neutral and non-ionic, the other form is either a weak acid or a weak base, and is therefore partly dissociated into ions. A solution of an indicator contains some of the neutral form A, some of the ionic form B, and the constituent ions of B. In the case of an acid indicator like phenolphthalein, the change can be represented by

$$\underset{\substack{\text{colourless} \\ \text{Neutral}}}{P'H} \rightleftharpoons \underset{\text{Ionic}}{HP} \rightleftharpoons H^+ + \underset{\substack{\text{red} \\ \text{Ions}}}{P^-}$$

The nature of the change in molecular structure may be illustrated by the case of phenolphthalein


Neutral form
colourless


Ionic form
red

On the addition of hydrogen or hydroxyl ions to the indicator solution, the equilibria between the two forms and the ions of the indicator are shifted. The alteration in the relative proportions of the two coloured constituents may cause a perceptible change in the colour of the solution. Thus the addition of hydrogen ions to a red phenolphthalein solution throws back the ionization thus

$$H^+ + \underset{\text{Red}}{P^-} \rightarrow HP \rightarrow \underset{\text{Colourless}}{P'H}$$

The colour of the indicator solution is completely discharged if sufficient hydrogen ions are added.

By applying the law of mass action to the phenolphthalein equilibria, it follows that

$$[P'H] = K_1[HP], \text{ and } K_2[HP] = [H^+][P^-]$$

i.e.
$$\frac{[P'H]}{[P^-]} = \frac{K_1}{K_2}[H^+] = K[H^+]$$

The relative proportion of the colourless and the red form of the indicator is proportional to the hydrogen ion concentration, i.e. the *p*H value of the solution controls the relative proportion of the two forms. A similar relationship applies to other indicators.

For an indicator to change colour when the *p*H of its solution is altered, a comparatively large variation must be caused in the relative proportion of the two coloured forms. In most indicators, the complete visible change corresponds with conversion from about 10 per cent in one form to about 90 per cent in that form. The perceptible change extends over about one or two units of *p*H; the more sensitive the indicator, the narrower being the range of change. The sensitivity depends partly on the colour of the indicator, for some colour changes can be seen more clearly than others. For indicators in which one form is colourless, the visible change depends also on the concentration of the indicator. Thus the first pink of phenolphthalein can be seen at *p*H 8·0 with a 0·007 per cent solution of the indicator, although under more usual circumstances (approximately 0·004 per cent solution) it is not seen until *p*H 9·0.

The *p*H value at which the visible change of an indicator takes place depends on the strength of the acid (or base) form of the indicator. If the acid (or base) form of the indicator is fairly strong, the colour change will occur not far from neutrality (*p*H 7), but indicators which are weaker as acids or bases change in solutions of *p*H values further from 7. The colour changes of the different indicators cover the whole range of acidity and alkalinity from *p*H 0 to *p*H 14.

### Applications of Indicator Action

Indicators are used officially—

(1) To control acid and alkali impurities in official substances (p. 135).

(2) To indicate the *end-point* of titrations in volumetric analysis (*a*) for reactions between acids and bases, and (*b*) for titrations in which a weak acid or base is displaced from its salt by reaction with a strong acid or base, e.g. for the titration of sodium carbonate or sodium borate with sulphuric acid. Theoretically the end-point of the titration should indicate when the reactants have been added in chemically equivalent proportions, but in practice the end-point observed is sometimes slightly different from the actual point of chemical equivalence. The difference is so small that it is quite negligible under ordinary circumstances. Thus in the titration of N hydrochloric acid with N sodium hydroxide solution, when the reactants are present in chemically equivalent proportions a solution of *p*H 7 is obtained. Methyl orange changes at *p*H 4·0, so that at the experimental end-point there is therefore a slight excess of acid. The amount in excess is not appreciable under ordinary titration circumstances, as it corresponds to the equivalent of about 0·01 mil of N acid in excess in a titration volume of 100 mils.

The most accurate indicator to choose for any reaction is that whose colour change occurs nearest the theoretical end-point of the reaction, i.e. the indicator change should correspond to the *p*H value of the solution of the product of the reaction under the experimental conditions. Thus in the titrations represented by the following equations, the most accurate indicators are those whose colour changes correspond with solutions of sodium chloride, sodium oxalate, carbonic acid, and boric acid respectively.

$$NaOH + HCl = NaCl + H_2O$$

$$2NaOH + H_2C_2O_4 = Na_2C_2O_4 + 2H_2O$$

$$Na_2CO_3 + H_2SO_4 = Na_2SO_4 + H_2O + CO_2$$

$$Na_2B_4O_7 + H_2SO_4 + 5H_2O = 4H_3BO_3 + Na_2SO_4$$

Owing to hydrolysis (cf. p. 53), sodium oxalate, like other salts of strong bases and weak acids, does not form a neutral solution, and the indicator must be chosen accordingly (cf. also titration of phosphoric acid and its salts, p. 205). A solution of boric acid (N/10) has a *p*H value of 5·2, while a saturated solution of carbon dioxide has a *p*H value of 4·5, so that methyl orange is a suitable indicator for the titrations of sodium carbonate and of borax.

When titrating a strong acid with a strong base, it is often not convenient to use an indicator which changes at the theoretical end-point (*p*H 7), as carbon dioxide may be present in the solutions and interfere with the end-point. Methyl orange is used because this indicator is not affected by the presence of carbon dioxide.

The indicators used for the official acid-alkali titrations have been chosen in accordance with the above principles. In general, an indicator may be replaced by any other indicator whose colour change occurs within the same *p*H range. In some cases, the end-point with the chosen indicator is difficult to determine. Under these circumstances, a solution containing the appropriate indicator can be prepared of a *p*H corresponding to the theoretical end-point. The titration is then continued until the indicator colour matches the standard colour (cf. official assay of Sodium Phosphate, p. 207).

## OXIDATION-REDUCTION POTENTIALS

When an inert metal such as platinum is placed in a solution containing two ions formed from the same metal in two different valency states (such as ferrous and ferric), the inert metal acquires an electric potential whose magnitude is controlled by the tendency of the two ions to change their valencies with the accompanying release or capture of an electric charge.

$$Fe^{+++} \rightleftharpoons Fe^{++} + (+)$$

The same argument applies to other pairs of substances one of which is obtained by oxidation of the other and conversely, the second is the result of reducing the first. If the tendency to change to the reduced form is greater than the opposite tendency the metal will become positively charged. This happens in solutions possessing oxidizing properties. Correspondingly the metal becomes negatively charged in solutions possessing reducing qualities. The sign and magnitude of the charge taken up by an inert metal in a solution is thus a measure of its oxidizing or reducing power. The potential acquired by the metal is known as the oxidation/reduction potential of the system. The oxidation/reduction potential obtained depends, of course, on the relative concentrations of the oxidized and reduced substances as well as their chemical nature; but a value can be defined which expresses only the chemical oxidation/reduction tendencies. This is the electrode potential ($E_0$) when the two forms are of equal concentrations, and it is related to the electrode potential ($E$) for any other solution by the equation

$$E - E_o = \frac{RT}{nF} \log_e \frac{C_o}{C_r}$$

where $C_0$ and $C_r$ are the concentrations of the substance in the oxidized and reduced forms respectively, $R$ is the gas equation constant, $T$ the absolute temperature, $F$ the Faraday, and $n$ the number of negative charges lost when the reduced form is converted to the oxidized.

## HYDROLYSIS OF SALTS

Solutions of the salts of strong acids with strong bases are usually neutral in reaction, but solutions of salts of strong acids with weak bases or salts of strong bases with weak acids are, respectively, acid (e.g. aluminium sulphate) and alkaline (e.g. sodium acetate) in reaction. The salt is said to be hydrolyzed.

$$CH_3.COONa + H_2O = CH_3.COOH + NaOH$$

In terms of the ionic theory, the hydrolysis of salts is explained thus—

Consider the case of sodium acetate, the salt of a weak acid with a strong base. As salts are almost completely ionized in solution, the solution contains a large concentration of acetate ions when the sodium acetate is first dissolved. But as acetic acid is only partially dissociated, some of these acetate ions react with the hydrogen ions of the water in accordance with the equation

$$CH_3.COO^- + H^+ \rightarrow CH_3.COOH$$

The resulting solution therefore contains an excess of hydroxyl ions and is alkaline in reaction.

$$CH_3.COONa + H_2O = CH_3.COOH + Na^+ + OH^- \qquad (a)$$

Similarly salts of weak bases and strong acids contain an excess of hydrogen ions and are therefore acid in reaction.

The degree of hydrolysis of a salt of a weak acid and a strong base can be calculated from the magnitude of the dissociation constant of the acid thus—

The equilibria

$$CH_3.COOH \rightleftharpoons CH_3.COO^- + H^+$$
$$H^+ + OH^- \rightleftharpoons H_2O$$

are controlled by the equations

$$\frac{[CH_3.COO^-][H^+]}{[CH_3.COOH]} = K_1$$
$$[H^+][OH^-] = K_w$$

It follows that

$$\frac{[CH_3.COOH][OH^-]}{[CH_3.COO^-]} = \frac{K_w}{K_1}$$

If one equivalent of the salt is dissolved in $v$ litres of solution and a fraction $x$ is hydrolyzed, it follows that—

$$[CH_3.COOH] = \frac{x}{v}$$

$$[CH_3.COO^-] = \frac{1-x}{v}$$

$$[OH^-] = [CH_3.COOH] = \frac{x}{v} \text{ (\textit{equation a}, p. 53)}$$

$$\therefore \frac{K_w}{K_1} = \frac{\frac{x}{v} \times \frac{x}{v}}{\frac{1-x}{v}} = \frac{x^2}{(1-x)v}$$

This equation enables the degree of hydrolysis of any salt of a strong base with a weak acid to be calculated at any dilution. It leads to the conclusions: (1) the weaker the acid (i.e.

TABLE VI

| Substance | Approximate $pH$ of N/10 Solution |
|---|---|
| *Acids*— | |
| Hydrochloric acid | 1·0 |
| Phosphoric acid | 1·5 |
| Acetic acid | 2·9 |
| Carbonic acid | 3·8 |
| Boric acid | 5·2 |
| *Alkalis*— | |
| Sodium hydroxide | 13·0 |
| Ammonia | 11·3 |
| *Salts*— | |
| Sodium chloride | 7·0 |
| Sodium citrate | 9·0 |
| Sodium acetate | 9·7 |
| Sodium bicarbonate | 8·4 |
| Sodium carbonate | 11·6 |
| Sodium dihydrogen phosphate | 4·5 |
| Disodium hydrogen phosphate | 9·2 |
| Trisodium phosphate | 11·9 |

the smaller the value of $K_1$) the greater is the hydrolysis of the salt, (2) the degree of hydrolysis of a salt increases as the solution becomes more dilute.

Similar equations and conclusions apply to salts of weak bases with strong acids. The hydrolysis of salts of weak acids and weak bases follows different rules, and is practically independent of the dilution of the solution.

The titration curves in Fig. 2 (p. 45) indicate the departure from neutrality of solutions containing equivalent quantities of sodium hydroxide and the weak acids, acetic and carbonic acids. Table VI also indicates the extent of hydrolysis of different salts.

## PRECIPITATION OF SALTS AND THE SOLUBILITY PRODUCT

According to the ionic theory, the precipitation of an insoluble salt is determined by the union of the ions of the salt, e.g.

$$Ag^+ + Cl^- \rightleftharpoons \underset{\text{dissolved}}{AgCl} \rightleftharpoons \underset{\text{precipitated}}{AgCl}$$

If the law of mass action is applied to these equilibria, the following equation is obtained

$$\frac{[Ag^+][Cl^-]}{\underset{\text{dissolved}}{[AgCl]}} = \text{constant}.$$

Since silver chloride is only very slightly soluble, the active mass or concentration of dissolved silver chloride *molecules* is constant. The equation becomes therefore

$$[Ag^+][Cl^-] = \text{constant } (S)$$

The constant $S$ is called the *solubility product* of silver chloride. Its value determines the solubility of silver chloride in any aqueous solution, for in any solution as soon as the product of the concentrations of the two ions exceeds the solubility product, precipitation takes place.

From the solubility product equation (which has been verified experimentally) it may be deduced that (1) the presence of excess silver ions (e.g. as silver nitrate) diminishes the solubility of silver chloride, since the concentration of chloride ions remaining in the solution is reduced in order to keep the ionic product constant; (2) the presence of excess chloride ions similarly diminishes the solubility of silver chloride.

The solubility of any precipitated salt is diminished by the presence in the solution of excess of a common ion (e.g. a saturated solution of barium sulphate in dilute hydrochloric acid gives a precipitate on the addition of either sulphuric acid or barium chloride). This principle is often applied in chemical analysis, e.g. in gravimetric analysis, where excess of the precipitating ion is always present; in the applications of insoluble salts (e.g. silver chromate) as indicators in colorimetric analysis; in the detection of impurities, and in the use of hydrogen sulphide as a precipitating agent in qualitative analysis.

SILVER CHROMATE AS INDICATOR

The precipitation of silver chloride and silver chromate by silver nitrate from solutions containing soluble chlorides and chromates depends on the equilibria

$$Ag^+ + Cl^- \rightleftharpoons \underset{\text{dissolved}}{AgCl} \rightleftharpoons \underset{\text{pptd}}{AgCl}$$

$$2Ag^+ + CrO_4^{--} \rightleftharpoons \underset{\text{dissolved}}{Ag_2CrO_4} \rightleftharpoons \underset{\text{pptd}}{Ag_2CrO_4}$$

The following relationships must be obeyed when the silver chromate just begins to be precipitated

$$[Ag^+][Cl^-] = S_1$$

$$[Ag^+]^2[CrO_4^{--}] = S_2$$

$$\text{i.e.} \quad \frac{[Cl^-]^2}{[CrO_4^{--}]} = \frac{S_1^2}{S_2} = \frac{(1{\cdot}56 \times 10^{-10})^2}{3{\cdot}34 \times 10^{-12}} = \frac{1}{1{\cdot}4 \times 10^8}$$

The experimental value of the constants $S_1$ and $S_2$ is such that, under normal titration conditions, less than 0·001 per cent of the chloride remains in the solution when the end-point is reached and silver chromate begins to be precipitated.

### PRECIPITATION OF SULPHIDES

The equation for the precipitation of the sulphide of a bivalent metal X is

$$XCl_2 + H_2S \rightleftharpoons XS + 2HCl$$

i.e.

$$X^{++} + S^{--} \rightleftharpoons \underset{\text{dissolved}}{XS} \rightleftharpoons \underset{\text{pptd.}}{XS}$$

From the equations the solubility product relationship follows, and this determines the conditions of precipitation of the sulphide.

$$[X^{++}][S^{--}] = S$$

Hydrogen sulphide is a weak acid, ionized to an extent depending on the hydrogen ion concentration of the solution. The ionization is represented by the equations

$$H_2S \rightleftharpoons H^+ + HS^- \rightleftharpoons 2H^+ + S^{--}$$

By applying the law of mass action to the above equilibria, the following expression may be derived

$$\frac{[H^+]^2[S^{--}]}{[H_2S]} = k$$

Therefore the concentration of the sulphide ion in a solution saturated with hydrogen sulphide is controlled by the hydrogen ion concentration or degree of acidity of the solution.

In strongly acid solutions, the sulphide ion concentration is low, so that only the metal sulphides which have a very small value of the solubility product are precipitated (e.g. mercuric sulphide). In less acid solutions, the sulphide ion concentration is greater, so that sulphides of larger solubility product may be precipitated. By adjusting the acidity or alkalinity of the solution, the metals may be precipitated by hydrogen sulphide in the order of the solubility products of their sulphides.

In some solutions, some metals are partially converted into complex ions (cf. p. 299), e.g. copper in presence of soluble cyanides forms the complex cupricyanide ion

$$Cu^{++} + 4CN^- = Cu(CN)_4{}^{--}$$

In these solutions, the concentration of the unchanged metallic ion is very small, so that on saturating the solution with hydrogen sulphide, the ionic product of the metal sulphide (in the example, the product $[Cu^{++}][S^{--}]$) is less than the solubility product. No precipitation takes place. The use of potassium cyanide in the official limit test for lead is an example of the application of this principle (p. 128).

# CHAPTER IV

## EQUILIBRIA IN HETEROGENEOUS SYSTEMS

THE equilibria discussed above have been conditioned by chemical reactions between substances in the gaseous state or in solution. Under both conditions, the reaction mixture is uniform throughout (homogeneous equilibrium).

The following types of physical and chemical equilibria apply to *heterogeneous systems*, that is, equilibria in those cases where the *system* (i.e. the whole mixture of substances in equilibrium) can be divided into distinct parts. Each part (homogeneous in itself) is called a *phase*. Phases may be gaseous, liquid, or solid.

For example, when a little sodium chloride is added to water, it dissolves completely, and a homogeneous system is obtained. But if excess of salt is added, the solution becomes saturated, and some sodium chloride remains undissolved. The mixture is no longer homogeneous throughout, but consists of two parts, a homogeneous saturated solution of sodium chloride, and solid sodium chloride. This is an example of an equilibrium between one solid phase and one liquid phase.

Gases mix together to form a uniform mixture, so that in any system only one gaseous phase is possible. Many liquids are completely miscible to form a single homogeneous solution (single phase), e.g. ethyl alcohol and water are miscible in all proportions. Other pairs of liquids are not completely miscible, so that more than one liquid phase is present at equilibrium, e.g. a mixture of chloroform and water in equal proportions separates into two layers (two phases).

The number of solid phases present is usually equal to the number of solid substances present at equilibrium, the solid aggregate consisting of a mixture of separate crystals of each substance (cf. also p. 75.)

The conditions of equilibrium in a heterogeneous system are determined by (*a*) the number of individual substances present in the system, (*b*) the number of phases present at equilibrium. The types of equilibria discussed below refer mainly to cases of (1) a single substance only present, (2) mixtures of two substances. More complicated types of heterogeneous equilibria are discussed in the textbooks of physical chemistry.

## (1) Single Substance Present

### (a) EQUILIBRIUM BETWEEN THE GAS AND LIQUID PHASES

This refers to equilibrium between a pure liquid and its vapour. According to the kinetic theory, the molecules of the liquid are in constant haphazard motion. The kinetic motion of some of the molecules near the surface of the liquid carries them completely from the liquid into the vapour phase. Thus there is a constant stream of molecules leaving the liquid surface for the vapour. Similarly there is a constant tendency for molecules to return to the liquid from the vapour, so that eventually an equilibrium state is attained. At equilibrium, the rate of escape of the molecules into the vapour (vaporization) is equal to the rate of return of the molecules to the liquid (condensation).

The rate of return of the molecules to the liquid is determined by the pressure exerted by the vapour, and for every temperature there is a certain pressure of vapour for which the rate of return is equal to the rate of escape.

*At any temperature, the equilibrium vapour pressure of a liquid is constant.* The vapour pressure of a liquid increases with rise in temperature, owing to the greater tendency of the molecules to escape from the liquid by reason of the increased velocity of their kinetic motion.

When a liquid is placed in an enclosed space, it tends to evaporate until the pressure of the vapour above the liquid equals the equilibrium vapour pressure of the liquid at the particular temperature. If the temperature is then reduced, the pressure of the vapour is above the equilibrium vapour pressure at the lower temperature. Therefore, condensation tends to take place, until the pressure has been reduced to the equilibrium value. The condensation may be delayed in the absence of small drops of the liquid or dust particles to act as nuclei (cf. p. 87), and the vapour is then said to be *supersaturated.* A supersaturated vapour is not stable, and the introduction of particles to act as centres of condensation causes the formation of the liquid to take place.

### (*b*) EQUILIBRIUM BETWEEN THE SOLID AND THE LIQUID PHASES

Below a certain temperature, characteristic of the particular substance, the solid form is more stable than the liquid, which tends to solidify or freeze. Above that temperature the liquid is more stable than the solid. *The melting point of a substance is that temperature at which the solid and liquid forms of the substance are equally stable and can co-exist*

Very often it is possible to cool a liquid below the melting point without solidification taking place (*supercooling*). The supercooled liquid is then in a *metastable form* (cf. supercooled vapour): it changes into the solid state if a small crystal of the substance is introduced into it. In many cases, mechanical agitation causes supercooled liquids to solidify. Viscous liquids (e.g. glycerin, m.p. 20°C) are especially prone to supercooling.

It is not possible to superheat a solid substance above its melting point without transformation into the liquid.

#### *Effect of Pressure on Melting Point*

The melting point of a substance is affected slightly by pressure. Substances which expand on freezing have their melting point lowered by increased pressure (e.g. water: m.p. at 100 atmos. = – 0·07°C), while substances which contract on freezing have their melting point raised by increased pressure.

### (*c*) EQUILIBRIUM BETWEEN SOLID AND VAPOUR PHASES

Many solid substances have an appreciable vapour pressure, and consequently tend to volatilize. In those cases where the vapour pressure of the substance in the space surrounding the solid is below a certain equilibrium pressure, the substance tends to pass directly into the vapour phase without first melting (cf. iodine at room temperatures). This process is called *sublimation*. The equilibrium sublimation pressure at any temperature is characteristic of the solid. It increases with rise in temperature.

#### *Triple Point*

The variations of the melting point of the solid form of a substance, the vapour pressure of the liquid, and the sublimation pressure of the solid may be represented diagrammatically in curves (Fig. 3). These three curves intersect at a point *O* (the *triple point*).

Each curve in Fig. 3 represents the conditions of temperature and pressure under which two phases may co-exist (ice and water, ice and water vapour, water and vapour). At the triple point all three phases are equally stable and may co-exist. Only at the particular temperature (+ 0·07°C) and the particular pressure (4·6 mm) represented by that point can ice, water, and water vapour exist in equilibrium with one another.

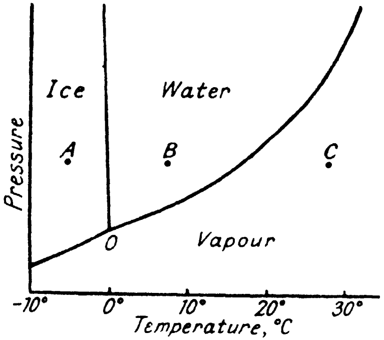


FIG. 3. TRIPLE-POINT OF WATER

The area between the curves in Fig. 3 represent the conditions of stability of single phases. Thus at the points represented by *A*, *B*, and *C*, only ice, water, and water vapour are stable respectively.

### (*d*) SUBSTANCES WHICH CRYSTALLIZE IN MORE THAN ONE FORM

Some substances crystallize in more than one form (*polymorphism*). In these cases, each type of crystal has its own characteristic melting point, and its own characteristic value for the sublimation pressure at any temperature. It is found that one solid form of the substance is more stable than the other solid form within a certain range of temperature, but outside this temperature range the second form is the more stable, e.g. at temperatures below 96°C, rhombic sulphur is more stable than monoclinic sulphur, but above that temperature monoclinic sulphur is more stable than rhombic sulphur. The temperature at which the two solid forms of the substance are equally stable (96°C in the case of monoclinic and rhombic sulphur) is called the *transition temperature*. At the transition temperature, both forms can remain together in stable equilibrium.*

The change from one solid form of a substance to a more stable solid form is often very slow. Sometimes it seems that the less stable form is apparently stable. For example, the ordinary metallic form of tin is less stable than grey amorphous tin below 18 C, yet it is only in exceptionally severe wintry climates that tin articles are found to show signs of the change.

## (2) Two Substances Present

### (*a*) SYSTEMS CONTAINING A LIQUID SUBSTANCE AND A GASEOUS SUBSTANCE

*Influence of an Inert Gas on the Vaporization of a Liquid*

When a liquid is placed in contact with an inert gas (e.g. the atmosphere), the escape of molecules from its surface is impeded by the presence of the gas, owing to the tendency of the escaping liquid molecules to be turned back by collision with the molecules of the gas. Thus the rate of conversion of the liquid into vapour is reduced considerably by the presence of the gas. But as the rate of return of vapour molecules to the liquid is reduced to an equal extent by the presence of the gas, the equilibrium vapour pressure of the liquid at the particular temperature is not altered.

When the gas pressure is much higher than the equilibrium vapour pressure of the liquid at the particular temperature, the conversion of the liquid into vapour proceeds slowly and gently (evaporation). But if, by raising the temperature of the liquid or by lowering the external gas pressure, the vapour pressure of the liquid becomes equal to the external gas pressure, the conversion of the liquid into vapour takes place freely, and the liquid boils.

As the temperature at which a liquid boils is dependent on the external pressure, liquids which decompose at temperatures corresponding with the boiling point under normal atmospheric pressures may be distilled safely at lower temperatures by reducing the pressure. Similarly, solutions of easily decomposed substances may be evaporated quickly at low temperatures under reduced pressure. These effects have important applications in many technical processes.

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* In the case of phosphorus, red phosphorus is the more stable form at all temperatures experimentally realizable, for the transition temperature lies above the melting point of that form.

### *Solubility of a Gas in a Liquid*

The solubility of a gas in a liquid is expressed by *Henry's law*, which states that *at constant temperature, the weight of a gas absorbed by a given weight of liquid is proportional to the pressure of the gas.* Henry's law is obeyed fairly accurately for gases which are only slightly soluble, e.g. oxygen and nitrogen in water. The behaviour of the moderately soluble and very soluble gases is represented less exactly by this law. The departure can be partially explained by chemical reactions taking place when the gas is dissolved.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$
$$NH_3 + H_2O \rightleftharpoons NH_4OH$$

*In a mixture of gases, which do not react together, the solubility of each gas is independent of the other gases, and varies proportionally with its partial pressure (Dalton's law).*

The solution in water of nitrogen and oxygen from the air may be taken as an example of the application of the laws of gaseous solubility.

| | Oxygen | Nitrogen |
|---|---|---|
| Relative solubilities . . | 0·04 | 0·02 |
| Ratio of partial pressures in air . . . . . | 0·21 | 0·79 |
| Ratio of weights dissolved . | $0{\cdot}04 \times 0{\cdot}21 = 0{\cdot}0082$ | $0{\cdot}02 \times 0{\cdot}79 = 0{\cdot}0158$ |

Hence the composition of the dissolved gases when removed from the water by boiling is 34·2 per cent oxygen, 65·8 per cent nitrogen, i.e. the proportion of oxygen is considerably increased.

The solubility of a gas in a liquid decreases rapidly with rise in temperature. All dissolved gases present in a liquid may be removed by boiling.

## (*b*) SYSTEMS CONTAINING TWO LIQUID SUBSTANCES

### *Mutual Solubility of Two Liquids*

Certain pairs of liquids, e.g. ethyl alcohol and water, form a single homogeneous solution when mixed together in any proportion. Such liquids are said to be *miscible in all proportions*. More often, however, pairs of liquids (e.g. chloroform and water) are not completely miscible. If a small quantity of the one liquid (e.g. chloroform) is added to the other (water) it dissolves completely to form a homogeneous solution. But if a larger quantity is added, the system separates into two layers (i.e. a two-phase system is formed). In the particular case mentioned the two layers consist of water saturated with chloroform, and chloroform saturated with water.

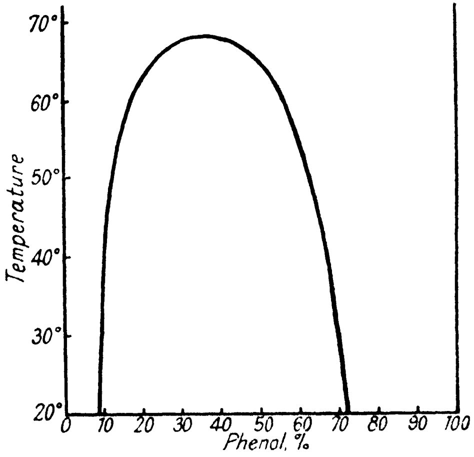

FIG. 4. SOLUBILITY CURVE, PHENOL-WATER

The proportion of the one liquid required to saturate the other depends on (*a*) the nature of the two liquids, (*b*) the temperature. If the liquids are chemically dissimilar (e.g. paraffin and water, or mercury and water) their mutual solubilities are generally small. Chemically allied liquids are often miscible in all proportions (e.g. methyl alcohol and ethyl alcohol, or ethyl alcohol and water).

The relationships between the relative solubilities of the liquids at different temperatures are conveniently represented by means of solubility curves.

Many pairs of liquids are partially miscible within a certain range of temperature, but completely miscible outside this range. Thus the solubility of water in phenol, and the solubility of phenol in water both increase as the temperature rises, until above a *critical temperature* (68·4°C) the two liquids become miscible in all proportions. (Fig. 4.)

In a few cases, the mutual solubility of the liquids decreases with rise in temperature, so that the liquids are only miscible in all proportions below a particular critical temperature. Thus at temperatures below 18°C triethylamine and water mix together in any proportion, but on warming the resulting solution, separation takes place into two layers.

### *Distillation of Liquid Mixtures*

(*a*) *Immiscible Liquids.* When two immiscible liquids (forming a two layer system) are heated, both substances tend to pass into vapour. The total vapour pressure above the mixture is equal to the sum of the pressures of the two vapours, i.e. the sum of the vapour pressures of the two liquids at the particular temperature. Therefore, if a mixture of water and an immiscible liquid (e.g. nitrobenzene) is heated, the mixture boils at a temperature such that

$$\text{Vapour pressure of water} + \text{vapour pressure of nitrobenzene} = \text{atmospheric pressure}$$

Thus the mixture boils at a temperature below the boiling point of either constituent. The product obtained by distilling the mixture contains water and nitrobenzene in proportions depending on their relative vapour pressures at the temperature of distillation.

If the vapour pressures of water and the immiscible liquid are $P_w$ and $P_s$ at the temperature of distillation, the relative proportions by weight of the two substances in the distillate is given by the equation

$$W_s/W_w = (P_s/P_w) \times (M_s/18)$$

where $W_w$ and $W_s$ represent the weights of water and the immiscible liquid in the distillate respectively, and $M_s$ and 18 represent the molecular weights of the immiscible liquid and water respectively.

The equation follows from Avogadro's hypothesis, which may be expressed in the form

$$\frac{P_s}{P_w} = \frac{\text{number of molecules of the organic substance per litre of vapour}}{\text{number of molecules of water per litre of vapour}}$$

Thus, the proportion of the immiscible liquid in the distillate is greatest for substances possessing a high molecular weight and high vapour pressure.

In accordance with this principle, a substance (which may not be very volatile, and consequently will not boil until a fairly high temperature is reached) may be *distilled in steam*, if it has a sufficiently high vapour pressure at temperatures in the neighbourhood of 100°C. Distillation in steam is used to separate certain organic compounds (especially those of aromatic type) from non-volatile compounds, e.g. aniline may be separated in this way from the metallic salts formed during the reduction process from nitrobenzene, p. 498 (cf. also the official assay of Solution of Cresol with Soap, p. 515). In some cases on an industrial scale, the distillation is effected using superheated steam and high pressures.

(*b*) *Partially Miscible Liquids.* The vapour pressure of a mixture of two partially miscible liquids, when present in proportions sufficient to form a two-layer system, is constant for a particular temperature. It is less than the sum of the vapour pressures of the individual liquids at the particular temperature.

The relative proportions of the two liquids in the vapour are constant for a particular temperature, so that when a mixture of this type is distilled, a liquid of constant composition passes into the receiver, as long as two liquid phases are present.

(*c*) *Miscible Liquids.* The vapour in equilibrium with a mixture of two liquids forming a single homogeneous solution contains both substances. But the proportion of the two substances in the vapour is usually different from the proportion of the two substances in the liquid. The behaviour of the liquid mixture is conveniently represented by curves relating the boiling point of the liquid mixture under normal pressure with the composition of the liquid and the composition of the vapour in equilibrium with one another at that temperature. Such curves are shown in Fig. 5.

Three different types of liquid mixture exist.

(1) The boiling point of *any* mixture of the two components lies between the boiling points of the pure liquids (e.g. methyl alcohol and water).

(2) A mixture of a certain composition has a *maximum boiling point* (e.g. hydrochloric acid and water, nitric acid and water).

(3) A mixture of a certain composition has a *minimum boiling point* (e.g. ethyl alcohol and water, ethyl alcohol and chloroform).

Each of these three types of liquid mixtures behaves in a characteristic manner on distillation.

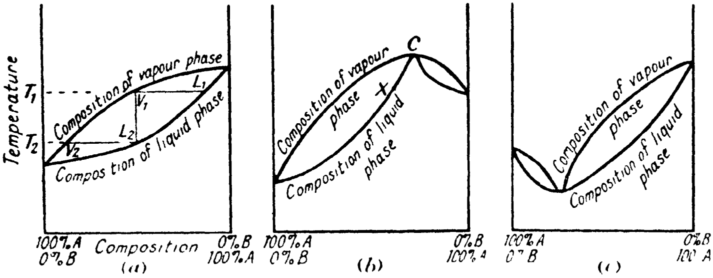
Temperature
$T_1$
$T_2$
Composition of vapour phase
$L_1$
$V_1$
$L_2$
$V_2$
Composition of liquid phase
100% A 0% B
Composition
0% B 100% A
(a)
C
Composition of vapour phase
Composition of liquid phase
100% A 0% B
0% B 100% A
(b)
Composition of vapour phase
Composition of liquid phase
100% A 0% B
0% B 100% A
(c)

Fig. 5. Boiling Points of Liquid Mixtures

*Distillation of Mixtures of Class* 1. When the mixture of the two liquids is boiled, the vapour which comes off contains a greater proportion of the more volatile constituent. Thus, the first distillate obtained by a simple distillation of the mixture contains an enhanced proportion of the more volatile constituent. The remaining liquid consequently contains an enhanced proportion of the less volatile constituent. As the distillation proceeds, the boiling point of the remaining liquid rises gradually, and the final fractions contain only the higher boiling fraction.

For example, the composition of the vapour obtained when a liquid of composition $L_1$ boils at a temperature $T_1$ is represented by the point $V_1$ (Fig. 5 (*a*) ). When this vapour is condensed completely, the liquid obtained has the composition $L_2$. This liquid contains a greater proportion of the more volatile constituent than the original liquid $L_1$.

By redistilling the first distillate, a product containing a still greater proportion of the more volatile constituent can be obtained. (The vapour obtained when a liquid of composition $L_2$ boils has the composition $V_2$.) But many tedious redistillations would be necessary to obtain a complete separation of the two liquids if their boiling points were close together. They may however be separated in one operation by distilling with the aid of a fractionating column (*fractional distillation*). (Cf. "Separation of benzene homologues," p. 487.)

A fractionating column consists of a long tube, which has a large cooling surface. The vapour escaping from the mixture being distilled is passed through this tube, where it is gradually cooled. Any liquid which may condense is returned to the vessel in which the original mixture is being heated. The vapour which escapes at the end of the fractionating column is collected.

*The action of the fractionating column* depends on the principles outlined above.

(*a*) Every time the rising vapour is cooled until partial liquefaction occurs, the liquid formed contains an enhanced proportion of the higher boiling component, which tends therefore to be returned to the heating vessel. The vapour passing on correspondingly contains an enhanced proportion of the more volatile component.

(*b*) Every time the falling condensed liquid is partially vaporized, the vapour formed contains an enhanced proportion of the more volatile component, and the residual liquid an enhanced proportion of the component of higher boiling point.

(*c*) When a cooled condensed liquid meets warmer ascending vapours, an interchange takes place between them, so that the vapour becomes enriched in the more volatile component and the liquid enriched in the higher boiling component.

Consequently, the vapour which escapes finally at the top of the fractionating column contains only the more volatile constituent. With an efficient column, almost the whole of this substance may be withdrawn from the mixture before the other component begins to distil.

The efficiency of a fractionating column depends on its length and the devices introduced to bring the descending condensed liquid and the ascending warm vapours into the closest possible contact.

*Distillation of Mixtures of Class* 2. It is not possible to separate completely by fractional distillation two substances which form a mixture of this type. A liquid represented by the point X on the curve (Fig. 5 (*b*) ) gives on fractional distillation a certain amount of the pure substance A. But as the residue becomes proportionally richer in B, the composition C is eventually reached. No further separation can be effected, as the liquid then distils unchanged and as a whole (*constant boiling mixture*).

Constant boiling mixtures are sometimes called *azeotropic* mixtures.

*Distillation of Mixtures of Class* 3. In this case, the constant boiling mixture has the lowest boiling point, and consequently distils first. No complete separation of the two components is possible.

## *Distribution*

When to a mixture of two liquids forming a two-phase system a third substance, soluble in both liquids, is added, that substance is present in both phases at equilibrium. For example, when iodine is shaken up with a mixture of chloroform and water, after the two layers have separated, iodine is present in the chloroform layer and in the water layer.

The relationship between the concentration of the third substance in the two phases is given by the *distribution law*, which was first stated by *Nernst*.

*At any temperature, the ratio of the concentration of the third substance in the one phase to its concentration in the other phase is a constant.* Symbolically, the law may be represented by

$$\frac{\text{Concentration in Phase 1}}{\text{Concentration in Phase 2}} = \text{constant } (K).$$

The constant $K$ is called the *distribution coefficient* or the *partition coefficient* of the substance between the two phases.

Very often the two liquid phases are composed of two liquids which are almost immiscible in one another, e.g. chloroform/water, benzene/water.

The distribution equation then becomes

$$\frac{\text{Concentration in Liquid 1}}{\text{Concentration in Liquid 2}} = K$$

The distribution equation applies to all cases of distribution, except when the substance undergoing distribution is in a different molecular state in the two phases. The modification to the equation can then be calculated.

For example, benzoic acid is present in water as single molecules ($C_6H_5.COOH$) (ignoring the small amount of ionization). But when benzoic acid is dissolved in a solvent such as chloroform, it is present mainly in a bimolecular form [$(C_6H_5.COOH)_2$].

$$2C_6H_5.COOH \rightleftharpoons (C_6H_5.COOH)_2$$

The distribution is controlled by the distribution of the single molecule form of the acid between the aqueous layer and the chloroform layer. The following relationship may then be deduced

$$\frac{\text{Concentration of benzoic acid in water layer}}{\sqrt{(\text{Concentration of benzoic acid in chloroform layer})}} = \text{const.}$$

*Extraction*

The distribution law is applied officially in the extraction of alkaloids from their solutions and preparations (cf. p. 577). When a solution of a free alkaloid in water is shaken with chloroform, and the layers allowed to separate, most of the alkaloid passes into the chloroform layer owing to the favourable magnitude of the distribution coefficient If the chloroform layer is separated, and the extraction of the aqueous layer is repeated several times, practically the whole of the alkaloid can be removed from the aqueous solution.

A more complete extraction is obtained when a series of successive extractions is made with small quantities of the extracting liquid, rather than a single extraction with a large quantity of the extracting liquid.

Suppose 1 g of an alkaloid is present in 100 mils of water, and it is desired to extract this alkaloid with 100 mils of chloroform. Suppose the distribution ratio of the alkaloid between chloroform and water is 20, i.e.

$$\frac{\text{Concentration of alkaloid in chloroform layer}}{\text{Concentration of alkaloid in water layer}} = 20.$$

Suppose the 100 mils of chloroform are shaken with the

100 mils of the alkaloidal solution. When the two liquid phases are separated, the fraction of the alkaloid in the chloroform layer is $(20/21) = 0{\cdot}95$. Thus 0·95 g is extracted by the chloroform.

Suppose now the chloroform is divided into four equal portions of 25 mils, and each 25 mils is used successively for an extraction. If a fraction $x$ of the alkaloid passes into the first chloroform layer (of volume 25 mils), the concentration of the alkaloid in that layer is $x/25$; the concentration of the alkaloid in the aqueous layer is $(1 - x)/100$. Therefore at equilibrium

$$\frac{\frac{x}{2}}{\frac{1-x}{100}} = 20, \text{ whence } x = \frac{5}{6}$$

The next extraction with another 25 mils of chloroform extracts five-sixths of the remaining alkaloid, so that the total fraction extracted in four successive extractions is

$$\frac{5}{6} + \frac{5}{36} + \frac{5}{216} + \frac{5}{1296} = \frac{1295}{1296}$$

Thus a total of 0·999 g of alkaloid is extracted.

Theoretically the larger the number of extractions and the smaller the portions of the extracting liquid, the more complete is the extraction for a particular volume of extracting liquid. In practice, the difficulties of handling and the possibility of losses in separating the two liquid layers control the number of extractions adopted in any particular case.

### (c) SYSTEMS CONTAINING A SOLID SUBSTANCE AND A LIQUID SUBSTANCE

#### *Solubility of a Solid in a Liquid*

When a solid substance is placed in contact with another substance in the liquid condition, the solid tends to *dissolve* in the liquid forming a *solution* of the solid in the liquid. The solid dissolves until the liquid is *saturated.* The saturated solution represents the only condition under which the solid and the solution can remain together in equilibrium.

*The solubility of a solid in a liquid at any temperature* may be defined as *the weight of the solid dissolving in* 100 *g of the liquid to form a saturated solution, at that temperature.*

The solubility of most substances increases with rise in temperature (cf. Fig. 20, p. 199). Thus a solution saturated at a higher temperature contains a greater proportion of the solid than is required to saturate the solution at a lower temperature. When such a solution is cooled, the excess of solid tends to crystallize out. But sometimes in the absence of minute crystals or dust particles to act as nuclei to start crystallization, the separation of the solid is delayed (cf. p. 87). The resulting solution is said to be *supersaturated.* Supersaturated solutions are metastable, and vigorous shaking or the introduction of nuclei causes crystallization to take place. Solid is then deposited until the stable saturated solution remains.

When the solubility of some substances (e.g. sodium chloride in water) is measured at different temperatures, and the measurements are plotted in the form of a solubility curve, the curve is found to consist of two or more parts. (Instead of being perfectly smooth, the curve suffers a sudden change of direction at a certain temperature, Fig. 6.) It is found in these cases that the solid substance in equilibrium with the solution undergoes a change in composition at the particular temperature. For example, in the case of sodium chloride in water, it is found that the solubility curve (*EAB*, Fig. 6) shows a discontinuity at 0·2°C. If the crystals deposited from solutions below this temperature are analysed, they are found to consist of a hydrate of sodium chloride ($NaCl, 2H_2O$), while if the crystals deposited from solutions above this temperature are analysed, they are found to consist of anhydrous

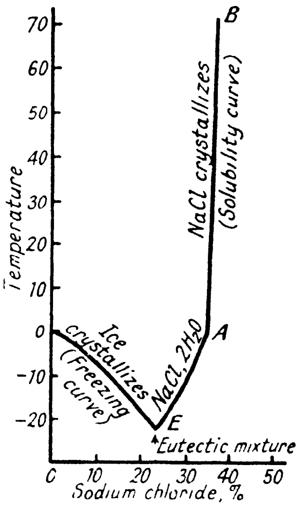

FIG. 6. FREEZING AND SOLUBILITY CURVES. SODIUM CHLORIDE-WATER

sodium chloride (NaCl). 0·2°C represents the transition temperature between solid sodium chloride hydrate and solid anhydrous sodium chloride (cf. p. 63).

*Purification by Recrystallization.* Many substances are purified by taking advantage of the differences in their solubilities at various temperatures. If a saturated solution of a substance (whose solubility is greatest at high temperatures) is prepared at a high temperature, and then cooled, the solid which crystallizes is pure. The impurities are contained in the *mother liquor* (which remains after the crystals have been separated), unless they also are present in sufficient quantity to saturate the solution. But if a substance is present which is chemically similar to the substance being purified, recrystallization may not result in separation owing to the formation of solid solutions (p. 75) (cf. copper sulphate and ferrous sulphate, p. 292). Substances whose solubilities increase rapidly with rise in temperature are most easily purified by recrystallization.

In order to obtain crystals of a uniform size, the solution may be supercooled to a certain extent, and the solution then seeded with uniform size small crystals. These crystals grow as the substance deposits on them from the supersaturated solution.

## *Freezing Point of Solutions*

The freezing point of a dilute solution is lower than that of the pure solvent by an amount dependent on the concentration of the solution (cf. p. 17). There is a certain concentration of solution which possesses a minimum freezing point. The minimum freezing point is called the *eutectic point.*

When a solution containing less dissolved substance than corresponds to the eutectic composition is frozen, the solid deposited consists of pure solvent crystals. The solution remaining therefore increases in strength, and eventually the eutectic composition is reached. Solutions of this composition crystallize as a whole, forming a mixture of crystals of the dissolved substance and crystals of the solvent (eutectic mixture). Solutions containing a greater concentration of dissolved substance than, corresponds to the eutectic composition, deposit on cooling crystals of the dissolved substance. Thus the solubility curve, the freezing curve, and the eutectic point may all be indicated on one diagram. Fig. 6 shows these curves in the case of sodium chloride and water.

The eutectic temperature and the relative proportions of the solvent and the dissolved substance in the eutectic mixture were once thought to be constant. It was concluded that the eutectic mixture represented a chemical compound between the solvent and the dissolved substance. It was shown later that the eutectic composition and temperature vary slightly when the pressure on the solution is altered. A further proof that the eutectic mixture is really a physical mixture can be demonstrated by microscopical examination of the deposited solid, when the different crystals of the solvent and dissolved substance can be seen lying beside one another.

*Purification of Liquids by Freezing.* Liquids may be purified by partially freezing them, for the first crystals which separate consist of the pure substance. These crystals can be separated, drained, and remelted, and, if necessary, purified further by refreezing (cf. purification of benzene, p. 488).

*Compound Formation Revealed by Freezing Point Determinations.* The freezing point curve for two substances which do not form a chemical compound with one another is of the simple single eutectic type (Fig. 6). But if the two substances (A and B) form a compound (AB), the freezing point curve shows two eutectics, one between the compound AB and pure A, and one between pure B and the compound AB. The highest temperature attained between the two eutectics represents the melting point of the compound AB.

The formation of compounds between two substances can therefore be detected by examination of the freezing points of mixtures of the two substances in various proportions. If more than one compound is formed between the two substances, these are revealed by the presence of the corresponding eutectic mixtures.

*Solid Solutions.* When a solution or liquid melt containing two substances is cooled, the crystals which are deposited usually consist of (*a*) one or other of the pure constituents, (*b*) a definite compound between the two constituents, or (*c*) a eutectic mixture.

Under certain conditions, if the substances are chemically allied, the crystals deposited on cooling the solution or liquid are all similar. The crystals are homogeneous, and contain both substances. The crystals are said to form *solid solutions.* A solid solution may be considered to be a single solid phase, as a homogeneous ordinary solution is considered to be a single liquid phase.

The formation of solid solutions indicates that the molecules of the one substance are sufficiently similar to the molecules of the other substance in structure and size for the molecules of the one to replace the molecules of the other in forming crystals. The replacements take place in a haphazard manner, so that homogeneous crystals containing both substances are obtained.

Substances which form solid solutions are said to be *isomorphous* with one another, for the crystals of the pure substances and of the crystalline solid solution have similar shapes and similar angles between the various crystal faces.

The various alums (p. 261) are isomorphous with one another. If a solution containing potash alum and chrome alum is crystallized, the crystals obtained contain both alums. The crystals are homogeneous, and vary in colour from white to deep violet depending on the relative proportion of the two alums in the solution.

Isomorphous crystals form *overgrowths* on one another. If a crystal of chrome alum is placed in a saturated solution of potash alum, the crystals becomes coated with the potash alum. The crystal form remains the same, and eventually an octahedral crystal is obtained with a violet core of chrome alum surrounded by colourless potash alum.

### (*d*) SYSTEMS CONTAINING A SOLID SUBSTANCE AND A GASEOUS SUBSTANCE

Some solids undergo a reversible chemical change with the formation of a gaseous substance; for example, the dissociation of calcium carbonate at high temperatures, and the dissociation of crystal hydrates at ordinary temperatures.

$$CaCO_3 \rightleftharpoons CaO + CO_2$$
$$BaCl_2, 2H_2O \rightleftharpoons BaCl_2 + 2H_2O$$

In cases of this type, it is found that the *equilibrium pressure of the gas formed by the dissociating solid is a constant at any particular temperature*, e.g. at any particular temperature, the equilibrium pressure of water vapour over hydrated barium chloride crystals has a definite constant value.

### *Deliquescence and Efflorescence*

Some crystal hydrates when exposed to the air tend to lose water, others tend to gain water, while many are quite stable and remain unaltered. The factors controlling the behaviour of the hydrate are (1) the aqueous vapour pressure in the air at the particular time, (2) the equilibrium aqueous vapour pressure of the crystal hydrate at the particular temperature, (3) the vapour pressure of the saturated solution of the hydrate in water at the particular temperature.

(*a*) *Aqueous Vapour Pressure of Hydrate Greater than Aqueous Vapour Pressure in Air.* Under these conditions, the crystal tends to lose water. A lower hydrate or the anhydrous salt is formed. For example, sodium carbonate decahydrate becomes converted into the monohydrate on standing in the air under ordinary conditions of humidity.

$$Na_2CO_3,\ 10H_2O \rightleftharpoons Na_2CO_3,\ H_2O + 9H_2O$$

This process is called *efflorescence.*

(*b*) *Aqueous Vapour Pressures of Hydrate and Saturated Solution Less than Aqueous Vapour Pressure in Air.* When the vapour pressure of the hydrate is less than the aqueous vapour pressure in the air, the hydrate tends to absorb water. The absorbed water dissolves some of the hydrate and forms a saturated solution. The vapour pressure of this solution is different from the vapour pressure of the hydrate at the same temperature. If the vapour pressure of the solution is below the vapour pressure in the air, the solution tends to absorb more water, which dissolves more hydrate. Eventually the whole of the hydrate passes into solution owing to absorption of water. This process is termed *deliquescence.*

(*c*) *Aqueous Vapour Pressure of Hydrate Less than Aqueous Vapour Pressure in Air, Vapour Pressure of Saturated Solution Greater than Vapour Pressure in Air.* Under these conditions, any water absorbed by the hydrate tends to be re-evaporated as soon as it forms the solution. Consequently the hydrate is stable.

In some cases, a lower hydrate may be converted into a higher hydrate by absorption of water from the air. Each hydrate has its own characteristic value for the equilibrium aqueous vapour pressure at any temperature. In these cases, the vapour pressures of the higher hydrate and its saturated solution determine whether any further change takes place after the formation of the higher hydrate.

### *The Phase Rule*

The generalization known as the *phase rule* defines the conditions under which heterogeneous systems are in equilibrium. The phase rule can be deduced theoretically from certain fundamental physical laws. It correlates the number of *phases* (P), *components* (C), and *degrees of freedom* (F) in any heterogeneous system in equilibrium by the relation

$$P + F = C + 2$$

The terms may be explained as follows—

(1) A phase is the homogeneous part of the heterogeneous system (cf. p. 59).

(2) The number of components is the least number of substances from which the system can be made up. For example, in the three-phase system, sodium chloride crystals, sodium chloride solution, water vapour in equilibrium together, the least number of substances from

which the system can be made is two (sodium chloride and water). The number of components is therefore two.

(3) In any equilibrium, it is possible to alter (*a*) the temperature, (*b*) the pressure, (*c*) the relative concentrations of the various substances present. It is found, in practice, that all of these variables cannot be altered independently at will. When a certain number of them (equal to the number of the degrees of freedom of the system) have been adjusted to particular values, the others take up definite unalterable values. When attempts are made to alter these values, the equilibrium is upset, and either one phase disappears or fresh phases are formed.

*Examples of the Application of the Phase Rule.* In the equilibrium between water and water vapour, the number of components (C) = 1 (water); number of phases (P) = 2 (liquid water, and water vapour)

$$P + F = C + 2 \text{ whence } F = 1 + 2 - 2 = 1$$

If the temperature of the system is adjusted to a particular value, at equilibrium there is a constant pressure of water vapour. The equilibrium pressure for the particular temperature cannot be altered. If the aqueous vapour pressure above the water is, by some means, increased, condensation of the surplus takes place. If it is decreased, water evaporates until, at equilibrium, the constant vapour pressure is attained. The system water + water vapour has one degree of freedom only, for as soon as a particular value is assigned to the temperature, the conditions of equilibrum of the system are fixed completely.

The system sodium chloride crystals, saturated solution, water vapour also has only one degree of freedom. [Number of phases = 3 (solid salt, saturated solution, and water vapour); number of components = 2 (sodium chloride and water).] When the temperature is chosen, only one fixed concentration of saturated solution is possible.

$$P + F = C + 2 \text{ whence } F = 2 + 2 - 3 = 1$$

The system formed by mixing alcohol and water has two degrees of freedom. [Number of phases = 2 (solution and vapour); number of components = 2 (alcohol and water).] Before the vapour pressures and all the other properties of the mixture in equilibrium are fixed, the relative proportion of the alcohol and the water, and the temperature must be assigned.

$$P + F = C + 2 \text{ whence } F = 2 + 2 - 2 = 2$$

Some systems have no degrees of freedom (invariant systems). Such systems can only remain in equilibrium when the temperature and pressure have fixed unalterable values. For example, water vapour, liquid water, and ice can only co-exist in equilibrium at a certain temperature and pressure represented by the point O in Fig. 3 (p. 62). [Number of phases = 3 (solid, liquid, and vapour); number of components = 1 (water).]

$$P + F = C + 2 \text{ whence } F = 1 + 2 - 3 = 0$$

# CHAPTER V

## COLLOIDS

When a simple substance is dissolved in a solvent, the dissolved substance is present in the solution as ions or single molecules, which are very small. But if the substance is broken down into small particles containing many molecules, the particles formed (if of a suitable size) may be suspended in a solvent to form what is known as a *colloidal solution*.

The properties of colloidal solutions are usually different from those of simple solutions. But as the properties of colloidal solutions depend on the size of the particles present, the line of demarcation between colloidal solutions and true solutions is not well defined. The properties of finely dispersed colloidal solutions (i.e. those with very small particles) approach those of solutions containing single molecules of substances with fairly large molecules (e.g. sucrose), and further, solutions of substances with very large molecules (e.g. proteins, p. 448) are definitely colloidal. Solutions containing particles (whether composed of one very large molecule or an aggregate of smaller molecules) of diameter between $1 \times 10^{-6}$ cm and $2 \times 10^{-5}$ cm approximately, may be regarded as typical colloidal solutions.

Owing to the comparatively large particle size (corresponding to a large apparent molecular weight) colloidal solutions have low osmotic pressure, and give small depressions of the freezing point and small lowerings of vapour pressure. For a similar reason, colloidal particles diffuse more slowly than the small molecules of true solutions. They are completely held back by suitable membranes through which the small molecules of dissolved substances are able to pass.

A colloidal solution may be freed from any dissolved substances present by *dialysis*. A membrane, permeable to the molecules of the dissolved substances but impermeable to the colloidal particles, is interposed between the colloidal solution and the pure solvent. The dissolved substance diffuses into the solvent.

The colloidal particles present in a colloidal solution may be separated by forcing the solution under pressure through a membrane impermeable to the particles. This process is known as *ultrafiltration*.

Substances containing colloidal particles exhibit the *Tyndall effect*. When light passes through a pure liquid or a true solution, nothing can be seen at right angles to the light beam. But when particles of a suitable size are present (as in a colloidal solution), the light is scattered by the particles, and the path of the light beam can be seen by the scattered light. (Thus the path of a beam of light passing through dust-laden air may be distinguished.) In the *ultramicroscope*, the presence of particles too small to be seen by the ordinary microscope is detected by the light they scatter. The particles present in most colloidal solutions are of ultramicroscopic dimensions.

The particles in a colloidal solution are prevented from settling by the *Brownian motion* (p. 11). The rate of settling of suspensions decreases rapidly when the particle size is diminished, and when the particles are small enough the rate of settling is so slow that the solutions are practically permanent.

## GENERAL METHODS OF PREPARATION OF COLLOIDAL SOLUTIONS

### Preparation by Dispersion

Colloidal solutions may be prepared by the breaking down of ordinary size fragments of the substance into particles so fine that they are able to remain in colloidal suspension. This may be effected by violent mechanical disruption (1) for some substances, by grinding in a colloid mill; (2) in the case of emulsions (p. 86), by shaking until one liquid phase is broken up into droplets; (3) for certain metals (e.g. gold) by electrical disruption. When an electric arc is struck under water between two pieces of the metal, the metal is disrupted into fine particles which form a colloidal solution in the water.

In some other cases, the substance is broken down and passes slowly into colloidal solution by simple contact with a suitable liquid which acts as the dispersion medium (p. 82), e.g. cellulose nitrate in the presence of acetone. This process is called *peptization*.

## Preparation by Aggregation

Colloidal solutions may also be prepared by forming the particles from smaller particles (usually single molecules of the substance). This may be effected by precipitating the substance under conditions such that it forms particles of a suitable size. The size of the particles, and thus the type of colloidal solution or the precipitate obtained, depends on the conditions of precipitation.

*Von Weimarn* investigated the conditions of formation of various types of precipitate. He showed that the type of precipitate formed depended on what is called the *dispersion coefficient* ($\delta$), which is defined

$$\delta = \frac{C}{s} \times \eta$$

where $s$ is the solubility of the substance, $\eta$ is the viscosity of the medium, and $C$ is the potential concentration of the substance at the instant of precipitation (e.g. if equal volumes of N barium chloride and N sulphuric acid solutions are mixed, at the instant of reaction there is a potential concentration of barium sulphate corresponding to an N/2 solution). The ratio $C/s$ is a measure of the degree of supersaturation of the solution immediately before precipitation takes place.

Von Weimarn's results may be outlined as follows —

(1) With very low values of the dispersion coefficient, i.e. with very dilute solutions, the solution is only just supersaturated. Precipitation is very slow, as only a few nuclei are present around which crystallization can proceed. A small number of large crystals are obtained.

(2) With rather greater values of the dispersion coefficient, i.e. with rather more concentrated solutions, more nuclei are formed. Precipitation is more rapid, and the crystals formed are smaller.

(3) As the value of the dispersion coefficient increases, i.e. with still more concentrated solutions, the nuclei become so numerous that only small particles are formed. If small enough, these particles remain in colloidal solution.

(4) With very large values of the dispersion coefficient, the solution sets to a jelly. The growth of the very numerous nuclei proceeds so fast that an interlacing network is formed (cf. structure of gel, p. 85).

By applying the above results, Von Weimarn was able to obtain colloidal solutions of typically crystalline substances not ordinarily obtained as colloidal solutions, and he was able to crystallize certain substances not known previously in the crystalline state. He prepared a jelly of barium sulphate by precipitation in 5N solution.

## CLASSES OF COLLOIDAL SOLUTION

The class to which a colloidal solution belongs depends on the physical nature of the suspended particles (solid, liquid, or gas), and also on the physical nature of the medium in which they are suspended. This medium is called the *dispersion medium*, the suspended particles constituting the *dispersed phase*.

The following types of colloidal solution are possible—

Solid dispersed in solid.
Solid ,, liquid, i.e. ordinary colloidal solution.
Solid ,, gas, i.e. smoke or dust.

Liquid ,, solid.
Liquid ,, liquid, i.e. emulsion.
Liquid ,, gas, i.e. mist.

Gas ,, solid.
Gas ,, liquid, i.e. foam.

The term "colloidal solution" is usually applied to the cases of solid dispersed in liquid systems. These colloidal solutions are divided into two classes, of which colloidal gold solution and gelatin solution are typical examples. Colloidal solutions of the first class are sensitive to the presence of electrolytes, which cause them to be thrown out of solution as precipitates. These are called the *lyophobic* colloidal solutions. The second type (the *lyophilic* colloidal solutions) are not precipitated by quite large quantities of electrolytes, and they are further distinguished from lyophobic colloidal solutions by forming viscous solutions which often set to a jelly.

Although there is a great difference in the typical properties of lyophobic and lyophilic colloidal solutions, colloidal solutions of intermediate character have been prepared. The two classes thus merge into one another.

## Lyophobic Colloidal Solutions

The particles in a lyophobic colloidal solution are electrically charged, and the stability of the colloidal solution is due to the electric charges. In the absence of the charges, two particles brought together by the Brownian motion would coalesce, so that the average particle size in the colloidal solution would gradually increase. Eventually the particles would become so big that they would settle as a precipitate. The presence of the electric charges (of the same sign on each particle) causes the particles to repel one another, and prevents them approaching close enough to cause coalescence.

The electric charge on the colloid particle is believed to arise from the presence of ions adsorbed (p. 90) from the solution on to the surface of the particle. If an ion of the opposite sign becomes adsorbed on to the particle surface, the charge on the particle is neutralized. When the electric charges on the colloid particles are removed in this way, there are no longer repulsive forces between approaching particles, and coalescence ensues. The particles *coagulate* into larger particles, and eventually separate as a precipitate.

Accordingly, lyophobic colloidal solutions are precipitated on the addition of electrolytes, the cation added neutralizing the charge on a negatively charged colloid (e.g. colloidal gold), while the anion is instrumental in neutralizing the charge on a positively charged colloid (e.g. colloidal ferric hydroxide).

Usually, the higher the valency of an ion, the stronger is its precipitating action, e.g. for negatively charged colloids aluminium sulphate is a more efficient coagulating agent than sodium sulphate. (Hence the efficiency of alum as a styptic.) But as the ion neutralizing the charge on the colloid particle must first be adsorbed on to the surface of the particle, and as adsorption effects are often highly specific, the efficiency of various substances as coagulating agents varies in a somewhat haphazard manner.

When two lyophobic colloidal solutions, whose electric charges have opposite signs, are mixed, the charges may neutralize one another so that both solutions are precipitated. For example, on mixing a solution of colloidal ferric hydroxide with a solution of colloidal gold, both colloids are precipitated. The mutual precipitation of oppositely charged colloidal solutions is of some importance in biological systems.

## Cataphoresis and Electric Endosmose

When electrodes connected to an electrical circuit are placed in a colloidal solution, the colloid particles are found to migrate either to the cathode or to the anode owing to the presence of the electric charges on the particles. This process is called *electrophoresis*. When the colloid particles are positively charged, they move to the cathode (cataphoresis), while if the particles are negatively charged they move to the anode (anaphoresis). [The passage of a liquid through a porous membrane under the influence of an electric field (*electric endosmose*) may be regarded as the converse of electrophoresis.]

### PROTECTION AND SENSITIZATION

If a colloidal substance of the lyophilic type (e.g. gelatin) is present in a lyophobic colloidal solution, the colloid particles of the latter become coated with a layer of the lyophilic colloid. As lyophilic colloids are comparatively insensitive to the addition of electrolytes, the coated lyophobic particle is correspondingly insensitive. Thus a solution of colloidal gold, which is normally coagulated by small quantities of electrolytes, is stable in the presence of considerable quantities of electrolytes if a little gelatin is added to the solution. This effect is called *protection*, and it enables stable colloidal solutions of sensitive substances to be prepared.

The efficiency of the various lyophilic colloids as *protective colloids* is compared by measuring the smallest quantity of each that must be added to a solution of colloidal gold to prevent precipitation on the addition of a specified quantity of an electrolyte.

Sometimes the addition of certain non-electrolytes (e.g. chloroform) to a colloidal solution renders the colloid more easily precipitated by electrolytes. This effect is called *sensitization*.

## Lyophilic Colloidal Solutions

Lyophilic colloids form solutions which are not easily precipitated by electrolytes. They form viscous solutions (the viscosity of which usually varies with the time of standing) which often set to a jelly (sometimes called the *gel* form to distinguish it from the ordinary *sol* form of the colloidal solution). In some cases (e.g. gelatin) the change from the sol to the gel form is reversible (e.g. by heating). In other cases (e.g. silica gel) the change is irreversible.

The particles present in lyophilic colloidal solutions are very highly solvated (i.e. they contain a large indefinite quantity of the dispersion medium). The stability of these colloidal solutions is due not so much to the presence of electric charges on the particles, but to the close relationship between the dispersion medium and the solvated colloid particles. Very often the particles in lyophilic colloidal solutions cannot be distinguished in the ultramicroscope, owing to the very small difference in refractive index between the dispersion medium and the solvated particles.

The viscosity and jelly forming properties of lyophilic colloids are due to the formation of thread-like particles (*fibrils*) which grow in length as the solution is allowed to stand. In time the growth of the fibrils is sufficient for them to form an interlacing network which confers the apparent rigidity on the jelly. The dispersion medium is retained in the interstices between the network of the fibrils (which are themselves highly solvated).

The viscosity of the solution varies with its age, for as the jelly partially forms, the network of fibrils resists relative motion. Stirring interferes with gelation owing to the breaking up of the jelly network.

The physical nature of the jelly depends on the coarseness of the fibrils present. A jelly composed of fine fibrils (e.g. silica gel) is more rigid and encloses less dispersion medium than a jelly composed of coarse fibrils (e.g. gelatin).

When jellies containing water are dried, the water lost first comes from the interstices of the fibrilar network, but strong desiccation may also remove water from the fibrils themselves. The swelling of gelatin in water is accompanied by diffusion of water into the gelatin fibrils. This swelling, like many other properties of gelatin, varies with the *p*H of the solution, as the state of the gelatin fibrils is determined by the amphoteric nature of the substance (cf. p. 449).

Many gels exude liquid on standing, the gel itself shrinking to a smaller volume. This phenomena is called *syneresis*. As the total volume does not change appreciably, it is not the simple reverse of the swelling on imbibition of liquid. The cause of syneresis has not yet been fully established.

Some colloidal solutions on standing form gels which change back again into mobile liquids on shaking. This phenomenon is called *thixotropy*. Thixotropic gels can be formed from suspensions of inorganic substances (e.g. alumina, clay) in water, provided electrolytes are present in the correct concentration. Some organic substances can also form thixotropic gels. It is believed that in these cases gels can only arise if the particles are built up into a jelly structure with molecules or groups of molecules arranged in a special way (e.g. it may be the molecules would have to be arranged parallel to one another). With large particles this is a slow change, so gel formation is slow. If the adherence of the molecules is slight, the special arrangement is easily broken down mechanically, only to reform slowly on further standing. The phenomenon is related to the plastic behaviour of materials such as clays which exhibit viscous flow with a coefficient of viscosity which is not independent of the rate of relative motion within the substance. They flow more easily at high rates of relative motion than would be expected from their viscosity at low rates In this type of colloid, the particles are not spherical (in clays they are thin laminae) and high rates of motion cause the particles to orientate into flow patterns in which they offer less resistance to motion.

## EMULSIONS

When a liquid is dispersed in another liquid an *emulsion* is obtained. In the case of two insoluble liquids, such as paraffin and water, two distinct types of emulsion may be formed (particles of oil dispersed in water, i.e. oil-in-water emulsion, and particles of water dispersed in oil, i.e. water-in-oil emulsion). These two types of emulsion may be distinguished by the fact that only the oil-in-water emulsion is a conductor of electricity, and by the effect of oil-soluble and water-soluble dyes. These dyes are absorbed by water-in-oil and oil-in-water emulsions respectively.

The properties of emulsions are determined by the energy relationships at the boundary between the two liquids (the oil-water boundary). These energy relationships are exemplified by the existence of surface tension.

### Surface Energy

A molecule in the centre of a liquid is surrounded more or less uniformly by a large number of other molecules, so that the molecule is not attracted any more in one direction than in another. But a molecule at the surface suffers a resultant pull inwards, as there are no molecules outside to counteract the attractions of the molecules in the interior. This inward attraction, tending to pull the surface molecules into the interior of the liquid manifests itself as a tendency to make the surface of the liquid as small as possible. Thus in the absence of other disturbing factors (such as gravity) the shape of a liquid drop would be spherical. For a given volume, the sphere has the smallest surface area of any solid figure. In order to increase the surface area of a liquid, work is required to pull more molecules from the interior to the surface against the inward attractive forces. The surface of the liquid is said to possess *surface energy*.

Surface forces, due to the uni-directional attractions on surface molecules, arise whenever there is a boundary (or *interface*) between two phases, i.e. at the gas-solid, liquid-solid, solid-solid, gas-liquid, or liquid-liquid interfaces.

The fact that supersaturated solutions, supercooled vapours, etc., are often not converted into more stable conditions in the absence of nuclei to start crystallization or condensation, is determined by surface energy considerations. It can be deduced theoretically that because of the existence of surface energy, the solubility and vapour pressure of small particles of a substance are higher than the ordinary values. Thus unless large particles are present, precipitation or condensation cannot occur.

Correspondingly, when a precipitate consists of a mixture of fine and coarse particles, the solution in contact with the particles is saturated with respect to the larger particles but not for the smaller ones. Therefore the smaller particles tend to dissolve, only to be reprecipitated on the larger particles so that these grow at the expense of the smaller ones. A precipitate can therefore be granulated, so that it can be filtered without passing through the filter-paper, by allowing it to stand. The same effect is achieved more rapidly by precipitation at the boiling point or by maintaining the solution and the precipitate at the boiling point for some minutes.

## Surface Tension and Interfacial Tension

Usually the term *surface tension* of a liquid refers to the boundary between the liquid and its vapour or an inert gas. It is defined as the energy (measured in ergs) required to increase the area of the surface of the liquid by one square centimetre.

The term *interfacial tension* is understood to refer to the boundary between two liquid phases. It is defined as the energy required to increase the area of the interface between the two liquids by one square centimetre. The magnitude of the interfacial tension depends on the nature of the two liquids concerned. It is high for two liquids which are chemically dissimilar (e.g. liquid paraffin and water), and diminishes to zero for liquids which are completely miscible in one another. The interfacial tension between two liquids ($I_{AB}$) is given by the equation

$$I_{AB} = S_{A\ (\mathrm{sat.\ B})} - S_{B\ (\mathrm{sat.\ A})}$$

where $S_{A\ (\mathrm{sat.\ B})}$, and $S_{B\ (\mathrm{sat.\ A})}$ are the surface tensions of saturated solutions of liquid $B$ in liquid $A$, and liquid $A$ in liquid $B$ respectively. In many cases the two liquids are practically insoluble in one another so that the equation is simplified to

$$I_{AB} = S_A - S_B$$

where $S_A$ and $S_B$ are the surface tensions of the two liquids.

MEASUREMENT OF SURFACE TENSION AND INTERFACIAL TENSION. The surface tension of a liquid may be determined by measuring the height to which the liquid rises in a capillary tube of circular bore of known radius. The capillary rise for liquids which wet the capillary tube is correlated with the surface tension ($S$) by the equation

$$S = grh\rho/2$$

where $h$ is the capillary rise, $r$ is the radius of the capillary tube, $\rho$ is the density of the liquid, and $g$ is the acceleration due to gravity.

The surface tensions of two liquids may be compared by measuring the weight of the drops of the liquids which form at and fall from the same circular orifice. The surface tensions are related to the drop weights by the formula

$$\frac{\text{Surface tension of liquid 1}}{\text{Surface tension of liquid 2}} = \frac{\text{weight of drop of liquid 1}}{\text{weight of drop of liquid 2}}$$

By a modification of this method, the interfacial tension between two liquids may be determined by measuring the weight of the drop of one liquid forming at an orifice immersed in the other.

### APPLICATION OF INTERFACIAL TENSION TO EMULSIFICATION

Emulsification involves the breaking up of one liquid into a large number of small drops which are dispersed in the other liquid. The total surface area of these small droplets is very large. Emulsification therefore involves a large increase in the area of the liquid/liquid interface, and a correspondingly large increase in the total interfacial energy. If the interfacial tension between the two liquids is high (e.g. liquid paraffin and water), a stable emulsion cannot be produced, owing to the large increase in energy required for emulsification. But the addition of certain other substances (called *emulsifying agents*) enables stable emulsions to be obtained between these two ✓ liquids.

The emulsifying agent lowers the interfacial tension between the two liquids, so that the large increase in surface area can be achieved without the energy of the system being increased so far that the system becomes unstable. In order to act as an emulsifying agent, the substance must be strongly adsorbed to the liquid/liquid interface, and form over the boundary of the two liquids a stable skin which possesses considerable mechanical rigidity so that it is not easily broken or removed from the interface (cf. detergent action of soap, Fig. 27, p. 391).

In many cases, the nature of the emulsion produced for any pair of liquids depends on the emulsifying agent added. Thus, emulsions prepared using an alkali-metal soap as the emulsifying agent are usually of the oil-in-water type, while emulsions prepared using bivalent metal soaps as emulsifying agents are usually of the water-in-oil type. The causes of these differences have not yet been discovered.

There is no apparent limit to the relative volumes of the two liquids in an emulsion, for emulsions of the oil-in-water type have been prepared using sodium palmitate as the emulsifying agent, although the total volume of water present was only 1 per cent. In these cases the dispersion medium is reduced to a very thin continuous film surrounding each oil droplet.

## Adsorption ✓

The existence of surface energy, due to the inward attractions of the molecules in the interior on the molecules at a boundary between any two phases, confers certain abnormal properties on the boundary. For example, molecules of other substances tend to become attracted to the surface and form a layer covering it. This phenomenon is called *adsorption*.

*Ad*sorption should be distinguished from *ab*sorption which refers to effects penetrating into the interior of the substance.

As a consequence of the physical laws by which systems having the greatest stability possess the minimum energy, it may be predicted that if the surface energy of any boundary is lowered by the presence of another substance at that boundary, then that substance tends to be adsorbed to the boundary. Further, the most strongly adsorbed substances are those which cause the greatest diminution of surface energy. Conversely, substances which raise the surface energy of the boundary are not adsorbed to the boundary.

For example, the surface tension of a soap solution is less than the surface tension of water, i.e. soap lowers the surface energy of the water/gas boundary. It is therefore adsorbed to the boundary, so that the soap concentration at the boundary is greater than its concentration in the bulk of the solution. Conversely, sodium chloride raises the surface tension of water, and the concentration of the salt in the surface layers is less than its concentration in the bulk of the solution. The exact increase or decrease in concentration at the surface can be deduced theoretically from the values of the surface tensions concerned.

When an aqueous solution of sodium chloride is shaken with charcoal, it apparently increases in concentration. This is due to the fact that water is more strongly adsorbed than the salt on to the charcoal surface. On the other hand, a solution of picric acid treated similarly decreases in concentration, as the picric acid is preferentially adsorbed.

The use of charcoal as a purifying and decolorizing agent depends on its strong adsorptive power and large surface area owing to its porous nature. The impurities and colouring matters are adsorbed on to the charcoal surface. The medicinal use of kaolin depends on its power of adsorbing toxins.

Adsorbed films are held to the underlying surface by the physical and chemical attractions between the molecules in the film and the molecules of the surface. Most adsorbed films are only one molecule thick, i.e. the substance is adsorbed until the surface is completely covered by a unimolecular film of the adsorbed substance (cf. the adsorbed layer of soap around oil-drops, Fig. 27, p. 391).

In many cases, the molecules comprising the adsorbed unimolecular film are *orientated*, i.e. all the molecules are disposed in the same way with one particular part or group towards one side of the boundary between the two phases. Orientation is due to the preferential chemical attraction of the surface molecules for one particular part of the adsorbed molecule. Thus in the case of the soap film around oil-drops in water, the aliphatic chain of the soap molecule is preferentially attracted to the oil side of the boundary while the carboxylic soap radicle is attracted to the water. The molecules of the soap are orientated accordingly.

### APPLICATION TO HETEROGENEOUS CATALYSIS

The effects produced by heterogeneous catalysts (p. 22) are often caused by adsorption.

When the reactants are adsorbed in a unimolecular film on the surface of a catalyst, they are more active and more intimately in contact with one another than they are when in solution or in the gas phase. Consequently they react together more rapidly. The products formed by the reaction must not be strongly adsorbed on the catalyst surface, as they must pass from the catalyst surface, leaving it bare. It is then able to adsorb further quantities of the reactants, and thus cause further combination.

The order of a catalysed reaction often differs from the order expected from the ordinary equation, e.g. the rate of the reaction

$$2SO_2 + O_2 = 2SO_3$$

in the presence of a platinum catalyst is almost independent of the oxygen concentration. The oxygen is adsorbed so strongly by the platinum that the catalyst surface is kept almost completely covered with oxygen independently of the pressure of the oxygen in the gas phase.

If a substance is present which is very strongly adsorbed by the catalyst surface, that surface becomes coated with a film of the substance. If this substance does not take part in the reaction being catalysed, the reacting molecules can no longer reach the catalyst, whose activity consequently disappears. The catalyst is said to be *poisoned*. (Cf. action of arsenic as a poison for the contact process reaction.)

## SECTION II

# CONTROL OF PURITY OF OFFICIAL PHARMACEUTICAL SUBSTANCES

# CHAPTER VI

## CONTROL OF PURITY

PERFECTLY pure chemical substances have constant composition and constant properties. The degree of purity of a sample (or its composition, if a mixture) is indicated by comparing its composition and properties with those of the pure substance or substances. The following methods are used for the control of purity of substances of pharmaceutical importance—

(1) Measurement of the physical properties of the sample and comparison with those of the pure or tolerated specimen.

(2) Measurement of the chemical composition of the sample and comparison with that of the pure or tolerated specimen.

(3) The third method, more sensitive to small quantities of impurity than the two previous methods, involves individual tests for specific impurities.

## PHYSICAL METHODS

### (1) Melting Point and Freezing Point

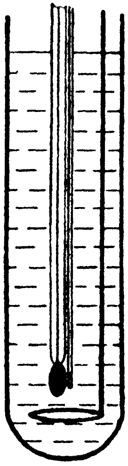

FIG. 7. MELTING POINT APPARATUS

The melting point of a substance is sensitive to the presence of impurities. An impure sample melts at a lower temperature than the pure substance, and further, it does not melt sharply, but over a range of temperature.

In order to minimize errors due to faulty experimental technique, the apparatus and procedure for the determination of melting points and freezing points are standardized. The methods adopted in the *British Pharmacopœia* may be classified under six headings.

(*a*) Substances easily reduced to powder.
(*b*) Substances not easily reduced to powder.
(*c*) Oil of Theobroma, Beeswax and Wool Alcohols.

(*d*) Hydnocarpus Oil, Lard, Soft Paraffin, and Wool Fat.

(*e*) Hard Paraffin and Cetostearyl Alcohol.

*f*) Fatty acids in soaps.

In classes (*c*) to (*f*) the substances contain more than one chemical individual, and the melting point serves to indicate the relative proportions of the constituents.

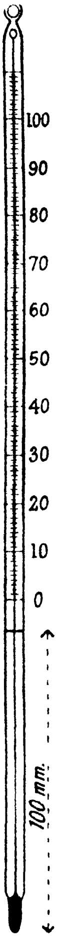

FIG. 8. CONSTANT IMMERSION THERMOMETER

### (*a*) MELTING POINT OF SUBSTANCES READILY REDUCED TO POWDER

The substances are dried without previous melting, powdered, and a small quantity introduced into a thin-walled capillary tube, sealed at one end. The tube is attached to a thermometer, close to the bulb, and immersed in a liquid which serves as a heating bath (Fig. 7). This is stirred continuously while the temperature of the bath is raised very slowly to allow for the slow conduction of the heat through the glass of the capillary tube. The temperature is read when the substance in the capillary tube is seen to be melting. (The thermometer must be standardized accurately, so that no errors arise from faulty calibration.)

#### *Correction of Emergent Column*

Most thermometers are calibrated when they are completely immersed in the heating liquid. When only the bulb is immersed, the mercury in the stem is cooler than if it were also immersed in the heating liquid. Its volume will be less, and therefore the reading of the thermometer will be too low. The error caused in this way may be overcome (1) by using a short stem thermometer with the mercury column completely immersed in the heating liquid, (2) by using a thermometer which has been calibrated for immersion to a certain mark, usually 100 mm from the bottom of the bulb (Fig. 8).

### (*b*) MELTING POINT OF SUBSTANCES NOT EASILY REDUCED TO POWDER

The substances in this class are: Eucalyptol, Glacial Acetic Acid, Menthol, Oil of Anise, Paraldehyde, Phenol, Thymol, Benzyl benzoate, Ethanolamine, and Nikethamide. A larger quantity of each of these substances is required for the determination.

The sample is placed in a test-tube, which is surrounded by a larger tube, the air jacket between the tubes serving to prevent too rapid conduction of heat, and therefore uneven and rapid cooling. The tubes are then placed in a freezing bath adjusted to a suitable temperature (Fig. 9).

The approximate freezing point of the sample is first determined, and the temperature of the bath is adjusted to be slightly (not more than 5°C) below this value. (This small difference ensures a slow cooling of the sample in the inner test-tube, and prevents excessive supercooling before crystallization occurs. If the degree of supercooling is not excessive, the temperature rises to the true freezing point when crystallization begins.)

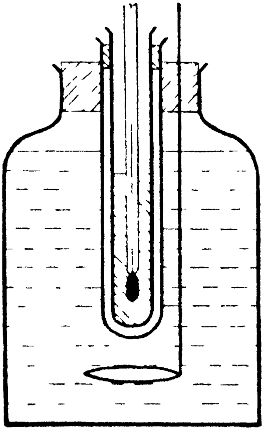

FIG. 9. FREEZING POINT APPARATUS

The sample is then cooled slowly to a temperature not more than 1° or 2° below the approximate freezing point. By stirring or by the introduction of a crystal of the solidified substance, crystallization is started, and the temperature rises to the freezing point, which is the highest temperature attained.

In those cases where the melting point of the sample is required, the tube containing the sample is now removed from the cooling-bath and allowed to warm. The melting point is taken as the temperature at which the liquid becomes clear and transparent. For pure substances the freezing point and the melting point are identical, but the experimental values may differ if supercooling has been excessive, in which case the apparent freezing point will be below the melting point.

### (c) MELTING POINTS OF OIL OF THEOBROMA, BEESWAX AND WOOL ALCOHOLS

The melting points of these substances are determined in the standard apparatus used for substances in Class (a) except that the capillary tube is left open at both ends. The melting points are taken as the temperatures at which the liquids rise in the capillary tube.

As it is necessary to melt these substances in filling the capillary tube, it is required that readings of the melting point should not be taken immediately.

These substances, like many other fatty substances, crystallize in more than one form, and the crystals first deposited on cooling the liquid belong to an unstable modification which melts at a lower temperature than the melting point of the more stable form. On standing the unstable form reverts to the stable, and the melting point returns to its normal value.

A similar procedure is necessary in the case of lard, before its melting point is determined by the following method.

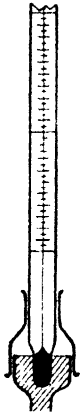

FIG. 10. SIMPLIFIED APPARATUS FOR MELTING POINT OF LARD

### (d) MELTING POINTS OF LARD, HYDNOCARPUS OIL, SOFT PARAFFIN, AND WOOL FAT

As these substances are mixtures of many compounds they have no definite melting point. They soften gradually and become fluid without any clear line of demarcation between the solid and the liquid states. The "melting point" is taken as that temperature (read by means of a thermometer embedded in the fat) at which they are fluid enough to allow the first drop to flow through an aperture in the bottom of a small glass cup filled with the sample (Fig. 10). The hole and the other dimensions of the cup are of standard size. The details of the official apparatus are given in the *British Pharmacopœia*.

### (e) MELTING POINT OF HARD PARAFFIN AND CETOSTEARYL ALCOHOL

The melting points (more accurately the congealing points) of these substances are determined by the method of cooling. When a molten liquid cools, and its temperature reaches the melting point, conversion takes place into the solid form, and the temperature remains constant until the whole of the liquid has been solidified. The temperature then begins to fall again.

The hard paraffin or the alcohol is melted in a tube, and a thermometer is placed in the liquid, which is allowed to cool with constant stirring. The temperature of the tube and its contents is read at frequent and regular intervals. It will be found that the temperature remains constant at a certain value for some minutes. This value is taken as the melting point of the substance. In Fig. 11 (*a*) the readings are plotted in the form of a cooling-curve, the horizontal portion representing the constant temperature, i.e. the melting point. Fig. 11 (*b*) shows the type of curve obtained when supercooling takes place.

### (*f*) MELTING POINT OF FATTY ACIDS IN SOAPS AND DETERMINATION OF CINEOLE

The melting points of the fatty acids in soaps are found in a similar way to the melting point of hard paraffin. Cooling is retarded by an air-bath, but considerable supercooling still occurs. Under these conditions the stationary range of temperature almost disappears, and the melting point is taken as the highest temperature reached after solidification commences. [Fig. 11 (*c*).]

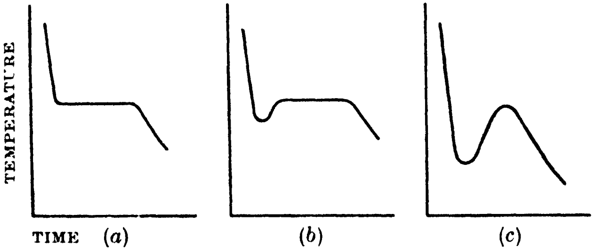

FIG. 11. COOLING-CURVES

*The cineole content* of some essential oils is determined by determining the freezing point using the same method and comparing it with the official tables.

## (2) **Boiling Point**

The boiling point of a liquid is strictly defined as that temperature at which its vapour pressure becomes equal to the atmospheric pressure over the liquid. For official purposes the boiling point of a liquid is taken as the range of temperature within which the whole, or a specified portion, of the substance distils.

The boiling point of a pure substance is as characteristic a physical constant as its melting point. Non-volatile impurities raise the boiling point (cf. p. 16), while the presence of volatile impurities also cause alteration (cf. p. 68). If the sample is pure, the whole will distil at the same temperature, leaving no residue. Impure liquids or mixtures of liquids often distil over a range of temperature, and may leave a residue of non-volatile impurities.

The details of the apparatus used for determining the boiling points of liquids are given in the *British Pharmacopœia.* The apparatus is designed to minimize errors arising from the following causes—

*Superheating of the liquid*, with its attendant difficulties due to "bumping," is avoided by placing a few pieces of porous pot in the distilling flask. These serve as nuclei for the formation of bubbles of the vapour, and ensure a steady boiling of the liquid.

*Superheating of the vapour* is prevented by heating the liquid only. This is effected by heating the bottom of the flask, which is encircled by an asbestos screen to prevent the vapour in the upper portion of the flask being heated.

Draughts may cause *uneven cooling and condensation of the vapour* on the walls of the distillation flask, and the whole apparatus is accordingly screened.

*The development of undue pressure* may take place if the vapour cannot escape freely from the distillation flask. This is prevented by controlling the rate of formation of the vapour (i.e. the rate of distillation), and by having the side tube of the distillation flask of a suitable size.

*The lag of the thermometer*, due to the slow interchange of heat between the vapour and the bulb of the thermometer, is compensated by controlling the rate of distillation and the dimensions of the apparatus.

*The emergent column error* of the thermometer is compensated by using a thermometer of the constant immersion type (p. 96).

## Correction to Standard Pressure

The observed boiling point depends on the particular barometric pressure at the time of experiment. For purposes of comparison this value must be corrected to standard conditions, i.e. 760 mm pressure. The influence of the barometric pressure on the boiling point varies according to the liquid, but for liquids of pharmaceutical importance the variations are not large. In general for these liquids an alteration in the barometric pressure of 10 mm causes a change in the boiling point of 0·4°C. (Acetone 0·38°C, and Chloroform 0·42°C.) The boiling point will be raised by this amount when the barometric pressure increases by 10 mm, while it will be lowered by a decrease in the pressure. Accordingly, the correction must be subtracted when the barometer reading is over 760 mm, and added when the barometer reading is below 760 mm.

### CORRECTION OF THE BAROMETER READING TO STANDARD CONDITIONS

The barometer reading must itself be corrected to standard conditions, before any correction can be applied to the boiling point of the liquid.

*Correction for Temperature.* Variations in temperature effect (1) the density of the mercury, (2) the length of the scale of the barometer. To allow for these variations, the observed readings of the barometer should be corrected to a standard temperature, which is chosen as 0 °C. The corrections to be made can be calculated from the known coefficients of expansion of mercury and of brass (from which the scale of the barometer is made). A table of corrections is given in the *British Pharmacopœia*, p. 715.

*Correction for Gravity.* The observed height of the barometer depends on the formula

$$\pi = g\rho h$$

where $\pi$ equals the barometric pressure, $h$ equals the height of the mercury column, $\rho$ equals the density of the mercury, and $g$ is the acceleration due to gravity.

The reading obtained depends on the value of $g$ at the place of observation, and must therefore be corrected to the standard value, which is the value at latitude 45° N or S ($g = 980{\cdot}665$ cm/sec$^2$). A table of corrections is given in the *British Pharmacopœia*, p. 716. The corrections are very small and except for places near the poles may normally be neglected. Theoretically, a correction should also be made to the barometer reading for the variation in the value of $g$ caused by the height of the place of observation above sea-level, but this correction is even smaller.

**Example.** A sample of carbon tetrachloride boiled at 76·1 °C, when the barometer read 740 mm, the barometer being read at a temperature of 16 °C at a place 55° N latitude.

Barometer correction due to gravity = + 0·63 mm.

Barometer reading after correction for gravity = 740·63 mm.

Correction of barometer reading for temperature = − 1·93 mm.

Barometer reading after further correction for temperature = 738·7 mm.

Departure of barometer reading from standard pressure = 760 − 738·7 = 22·3 mm.

$$\text{Correction of boiling point} = 0{\cdot}4 \times \frac{22{\cdot}3}{10} = +\,0{\cdot}89\,^\circ\text{C}.$$

*Corrected boiling point of carbon tetrachloride* = 76·1 + 0·89 = 76·99 °C.

If the corrections for gravity and the temperature of the barometer had been neglected, the calculated boiling points would have been 77·01 °C and 76·91 °C respectively.

### (3) Specific Gravity

The *specific gravity* of a substance is the ratio of the weight of the substance to the weight of the same volume of water, both weighings being made at 15·5°C in air. *The density* of the substance is the mass of a unit volume of the substance at a stated temperature. The unit of volume is the millilitre,* which is the volume occupied by 1 g of water at its point of maximum density (4°C) the weighings being taken *in vacuo.* Therefore there is a slight difference in the numerical values of the specific gravity and the density of the substance at the same temperature.

Officially the relation of weight to volume is expressed as weight per millilitre, determined by dividing the weight in air (expressed in grammes) of the quantity of the liquid which fills a pycnometer at 20°C by the capacity of the pycnometer at 20°C, expressed in millilitres. The capacity of the pycnometer is defined against water as a reference standard weighed against brass weights in air. The weight per millilitre differs slightly from true density owing to the buoyancy effects of the air.

There are two general methods for the determination of the specific gravity of *liquids*—

(1) By weighing a definite volume of the liquid in an apparatus (e.g. a pycnometer or specific gravity bottle) which enables a definite volume to be taken.

(2) By applying Archimedes's principle, that the upward thrust on a body immersed in the liquid is equal to the weight of the liquid displaced so that—

(*a*) a floating object of constant weight sinks to different depths in liquids of different specific gravities (principle of the hydrometer),

(*b*) a solid of definite volume weighs less immersed in a liquid than in air, by an amount proportional to the specific gravity of the liquid (principle of specific gravity balance).

For the determination of the specific gravity of solids there are two classes of method—

(1) A definite volume of the solid may be weighed. The volume can be determined by (*a*) geometrical measurement,

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* A millilitre is 1·000027 c.c.

(*b*) measuring (using a specific gravity bottle) the volume of a liquid which occupies the same volume as the solid, (*c*) application of Archimedes's principle. The difference in weight of the solid in air and immersed in a liquid of known specific gravity is proportional to the volume of the solid.

(2) A liquid of the same specific gravity may be prepared. Two miscible liquids are chosen, one less dense than the solid, the other heavier. By making a mixture of these liquids in a suitable proportion it is possible to obtain a liquid in which the solid will neither rise nor sink. The specific gravity of the solid is then equal to that of the mixture. The specific gravity of waxes may be determined by this method using mixtures of alcohol and water.

### (4) Refractive Index

When a ray of light passes from one medium to another it is refracted, i.e. it suffers a change of direction. The magnitude of the change depends on the refractive indices of the two media.

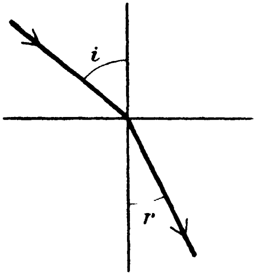


FIG. 12. REFRACTION OF LIGHT

The *Refractive Index* of a substance is given by the relationship

$$\sin i/\sin r = \mu$$

where $i$ equals the angle of incidence, and $r$ equals the angle of refraction (Fig. 12) when the light is passing from air (more strictly from a vacuum) into the medium of refractive index $\mu$.

When light passes from a medium of refractive index $\mu_1$ to a medium of refractive index $\mu_2$ it is refracted in accordance with the equation—

$$\sin i/\sin r = \mu_2/\mu_1$$

It follows that when light is passing from an optically lighter to a denser medium (i.e. $\mu_2 > \mu_1$), it is refracted towards the normal to the surface ($i > r$), and when it is passing from a denser to a lighter medium it is refracted away from the normal.

The refractive index of a pure substance is a physical constant, and can be conveniently measured by means of a *refractometer.* The more common forms of refractometer depend upon the determination of the *critical angle,* whose magnitude is related to the refractive indices of the media concerned.

## CRITICAL ANGLE OF REFRACTION

When light passes from a medium of refractive index $\mu$ into air, it is refracted away from the normal. If the angle of incidence is increased, the emergent beam lies closer to the surface, and if the angle of incidence is increased further, a stage is reached eventually when the light emerges at a grazing angle (Fig. 13). Light incident at angles greater than this critical value is unable to emerge at all, and is completely internally reflected.

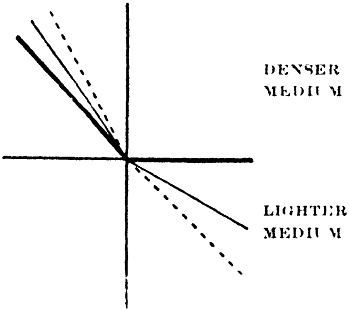


FIG. 13. CRITICAL ANGLE OF REFRACTION

The limiting angle of incidence above which light suffers complete internal reflection is called the *critical angle.* Its value is given by the equation

$$\sin i = 1/\mu$$

since $r = 90°$, and $\sin r = 1$.

For light passing from a medium of refractive index $\mu_2$ to a medium of refractive index $\mu_1$ (where $\mu_2 > \mu_1$) the critical angle is given by the equation—

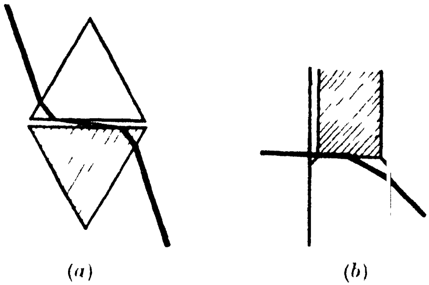
$$\sin i = \mu_1/\mu_2$$

### Principle of Refractometer

The critical angle is measured for refraction between a substance of known refractive index, and the substance whose refractive index is to be determined. The unknown refractive index can be calculated from the equation above.

*Determination of Critical Angle by means of Refractometer*

All light entering the optically denser medium from the less dense medium lies within the critical angle after refraction.



(a) (b)

FIG. 14. OPTICAL SYSTEMS OF REFRACTOMETERS
(a) Abbe, (b) Pulfrich

(This is shown in Fig. 13 when the direction of the light rays is reversed.) No light can enter to give angles greater than the critical angle, and therefore the region beyond the critical ray is dark. At the critical angle there is a sharp transition from light to darkness.

In the refractometer, light is incident on the boundary between the substance to be examined and an optically denser glass prism of known refractive index. Light only enters the prism from the less dense substance within the limits of the critical angle, so that this angle is indicated by a sudden change from light to darkness. A telescope is rotated to bring the light/dark boundary into view.

As the light emerges from the prism into the air, it is further refracted, so that the direction of the telescope departs from the original direction of the critical ray within the prism. A correction is made for the effect of this second refraction (Fig. 14).

In the *Abbé refractometer*, the unknown substance is examined as a thin liquid film between two glass prisms, the upper one possessing a ground glass face and serving to illuminate the film of liquid by light scattered in all directions. The critical angle for light entering the lower prism from the liquid is measured.

In the *Pulfrich refractometer*, the substance, if liquid, is placed in a cell on a glass prism. The boundary between the substance and the glass prism is illuminated at a grazing angle, and the light entering the prism is examined.

Many refractometers are calibrated so that the refractive index of the substance can be read directly.

### *Correction for Wave-length and Temperature*

The refractive index of a substance varies with the wave-length of the light used, and also with the temperature. For accurate readings, the refractometer must be used with monochromatic light, i.e. light of a single wave-length as distinct from white light which contains all wave-lengths. The Abbé refractometer can be used with white light to give a mean value of the refractive index, for although the boundary between light and darkness is normally coloured, a device is included to neutralize the colour, and to obtain a sharp boundary.

To avoid errors due to variation in temperature, the prisms and the substance under examination are surrounded by hollow jackets through which water at a constant temperature is kept in circulation.

The *Zeiss Butyrorefractometer* is a modified form of the Abbé refractometer designed for measurements on butter-fat. It has only a small range of refractive index, so that no adjustable compensating devices are necessary to neutralize any colours produced during the refractions.

## OFFICIAL APPLICATIONS OF REFRACTIVE INDEX MEASUREMENTS

The refractive index is used as a guide to indicate the purity of many liquids, including some of the essential and fixed oils and the waxes, and in the determination of the alcohol content of various preparations.

### *Determination of Alcohol Content*

Twenty-five mils of the preparation are diluted with 100–150 mils of water. Volatile substances other than alcohol, if present, are removed as described in the *British Pharmacopœia*. The solution is then distilled. The whole of the alcohol present in the 25 mils of the preparation is collected in the first 90 mils of the distillate. This is diluted to 100 mils, and the specific gravity and refractive index of the diluted solution are measured.

The refractive index and specific gravity of aqueous alcohols depend on the proportion of alcohol present. If a third substance is present as an impurity, the refractive index will correspond to a pure mixture containing a certain proportion of alcohol, while the specific gravity will correspond to a pure mixture containing a different proportion of alcohol. Therefore if the refractive index and specific gravity give values indicative of the same particular mixture of pure alcohol and water, it is improbable that any impurity is present. Under these conditions, the composition of the diluted alcohol can be ascertained, and the proportion of alcohol in the original preparation can be calculated. (Cf. *British Pharmacopœia*, p. 772.) The composition of Industrial Methylated Spirits cannot be determined from the official alcohol tables owing to the presence of the methylating agent.

## ✓(5) Optical Rotation

### The Nature of Polarized Light

Light consists essentially of a series of waves, the colour of the light being determined by the wave-length. (The wavelength of violet light is approximately 0·00004 cm. while red light at the other end of the visible spectrum has a wavelength of about 0·00008 cm.) *Plane polarized* light differs from ordinary light in that the wave-vibrations are confined to one plane only. Certain crystals (e.g. tourmaline) or an optical device such as a *nicol prism*, permit the passage of light vibrating in one plane only, and by passing ordinary light through them, polarized light is obtained.

*A nicol prism* is formed from a crystal of Iceland spar, by cutting it diagonally into two sections. The two halves are then cemented together, enclosing a thin film of Canada balsam or linseed oil.

Light polarized by one nicol prism passes through a second nicol prism if the polarizing planes of the two prisms correspond. If the second prism is rotated, the amount of light passing through decreases, until the polarizing plane of the second prism is at right angles to that of the first, when no light passes through at all. The nicol prisms are then said to be "crossed."

But if certain substances are interposed between the nicol prisms, light is able to pass through the second prism, which must then be rotated through a certain angle in order to obtain complete darkness. The plane of polarization has been rotated by the interposition of the substance. Substances which rotate the plane of polarization so that the second nicol prism must be turned to the right (i.e. in a clockwise direction when looking towards the source of the light) are said to be *dextro-rotatory*, while substances which rotate the plane of polarization to the left are said to be *laevo-rotatory*. The substances which rotate the plane of polarized light are said to be *optically active* (cf. p. 421).

The magnitude of the rotation observed is proportional to (1) the length of the layer of the substance through which the light is passed (the substance is usually examined in the pure state if it is a liquid, otherwise it is examined in solution); (2) the concentration, if the substance is examined in solution. The observed rotation also depends on the nature of the substance, as well as the temperature, and the wave-length of the light used.

The *optical rotation* of a pure substance may be defined as the rotation produced when the light passes through a layer of the substance 1 dm long. This quantity is usually given the symbol $\alpha$, the temperature and wave-length being indicated by suffixes, thus: $\alpha_D^{20°}$ where the symbol D signifies that sodium light (the D line of the spectrum) has been used for the determination.

The *specific rotation* of a pure substance (which is equal to the optical rotation divided by the density) is denoted by $[\alpha]$ and is defined in accordance with the equations—

$$[\alpha] = \alpha/d = a/(l \times d)$$

where $a$ equals the rotation when the light passes through a length $l$ of the substance ($l$ being measured in decimetres) and $d$ is the density of the substance. For a substance examined in a solution containing $c$ grammes per 100 mils, the specific rotation is given by the equation—

$$[\alpha] = \frac{a}{l} \times \frac{100}{c}$$

The specific rotation, being a characteristic physical constant, is used officially to control the purity of optically active substances, including many of the essential oils.

*The molecular rotation* of a substance is equal to its specific rotation multiplied by the molecular weight. It is a measure of the rotation caused by one molecule of the substance.

## MEASUREMENT OF OPTICAL ROTATION BY MEANS OF THE POLARIMETER

*The polarimeter* is represented diagrammatically in Fig. 15. Light of the appropriate wave-length (usually obtained from a sodium flame) enters the polarimeter by means of a system of lenses $A$, and is then passed through the first nicol prism

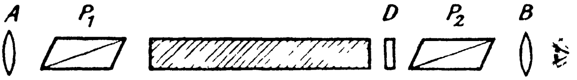


FIG. 15. OPTICAL SYSTEM OF POLARIMETER

$P_1$ (the polarizing prism or polarizer), which converts it into plane polarized light. The polarized light then passes through the tube containing the optically active substance or its solution. (The tubes are usually made exactly 1 dm, or some simple ratio of a decimetre in length, and are sometimes water-jacketed to ensure constancy of temperature.) The light then passes through the second nicol prism $P_2$ (the analysing prism or analyser, which is mounted so that it can be rotated), and finally into the eyepiece $B$.

The analysing prism is first set to darkness before the optically active substance is introduced into the light beam, and the rotation necessary to restore total darkness is measured after the substance has been interposed.

In actual practice it is rather difficult to set the analysing prism for complete darkness. Therefore a device $D$ is introduced into the light beam which divides it into two halves in such a way that the measurements are made when the two parts are of equal intensity. It is much easier to match the two halves of the field of view exactly than to estimate the position of minimum light.

The *saccharimeter* is a polarimeter with a scale graduated to read sugar concentrations directly. In some saccharimeters, the analysing prism does not rotate. The instrument is adjusted so that the two parts of the field of view are of equal intensity before the substance is introduced. After the substance has been introduced the two parts no longer match, and a quartz wedge is adjusted so that equality is restored. Quartz rotates the plane of polarized light. The instrument is designed so that the rotation due to the quartz is opposed to the rotation due to the substance being examined. By altering the position of the wedge, the light can be caused to pass through a varying length of quartz until the rotation due to the substance is exactly neutralized by that due to the quartz. From the position of the quartz wedge, the rotation due to the substance can be determined. The saccharimeter can be used with white light and for turbid solutions.

### (6) **Viscosity**

Viscosity is that property by virtue of which the motion of one part of a liquid relative to another part is resisted. When a liquid flows through a tube, the film of liquid close to the walls remains stationary, while the velocity reaches a maximum in the centre of the tube. Such a state of relative flow is opposed by the viscous forces.

Consider the forces on two parallel planes distance $d$ apart in a liquid showing differential flow. If the relative velocity of these two planes is $v$, the magnitude of the forces opposing the relative flow will be proportional to the velocity gradient, i.e. proportional to $v/d$. The stresses will operate tangentially to the planes, in a direction opposing their relative motion.

For any given liquid the following equation applies—

$$\text{Opposing stress} = \eta(v/d)$$

where $\eta$ is a constant characteristic of the liquid, and is called the *coefficient of dynamic viscosity.*

The coefficient of dynamic viscosity may be defined by the equation—

$$\eta = \frac{\text{stress}}{\text{velocity gradient}}$$

where the stress is the viscous force opposing the motion, acting on unit area of each of the two planes.

The unit of dynamic viscosity is called the *poise*, and from the equation it is seen that the poise is the viscosity of that liquid in which unit velocity gradient produces unit opposing stress. It may accordingly be defined as follows: *The poise is the viscosity of that liquid in which the tangential force exerted on each of two parallel planes (placed 1 cm apart in the liquid) is*

1 *dyne/cm*$^2$*, when one of the planes is moving in its own plane relative to the other with a velocity of* 1 *cm per sec.*

*The kinematic viscosity* is defined as the dynamic viscosity/density. The unit is the *stoke*, and a liquid has a kinematic viscosity of 1 stoke if it has a dynamic viscosity of 1 poise and 1 $cm^3$ weighs 1 g. The viscosities of the official substances are measured in centi-stokes (i.e. hundredth parts of a stoke).

## DETERMINATION OF VISCOSITY

The viscosity is used officially to control the composition of Pyroxylin and the Liquid Paraffins.

The viscosity of a liquid varies with the temperature and accordingly the experimental observations are made at specified temperatures.

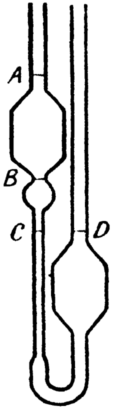


FIG. 16. OSTWALD VISCOMETER

### *The Ostwald Viscometer*

The Ostwald viscometer is illustrated in Fig. 16. It consists essentially of a series of bulbs connected by a length of capillary tube. The apparatus is constructed of glass, to standard dimensions.

It can be shown that the velocity of flow of a liquid through a capillary tube is given by the equation

$$Q = \frac{\pi r^4}{\eta L} P$$

where $Q$ is the rate of flow (the volume of liquid flowing past unit area per second) $r$ and $L$ are the radius and length of the capillary tube respectively, $P$ is the difference in pressure between the two ends of the tube, and $\eta$ is the coefficient of dynamic viscosity of the liquid.

An elaborate experimental technique would be necessary in order to determine the viscosity directly from this equation, as the quantities $r$ and $P$ are not easy to measure with sufficient accuracy, and as it is difficult to obtain a capillary tube sufficiently uniform in diameter. These difficulties are overcome by using a comparative method for the determination of viscosity.

When using the Ostwald viscometer, the liquid is made to flow through the capillary tube from the bulbs in one arm to the bulb in the other. The pressure ($P$) is therefore largely controlled by the difference in the liquid levels in the two arms. (If the difference in the level is $h$, the pressure will be $g\rho h$, where $\rho$ is the density of the liquid.)

If the same viscometer is used under exactly the same conditions for two different liquids (using the same volumes, and allowing to flow between the same fixed marks on the viscometer) the rates of flow will be related by the equation—

$$\frac{\text{Rate of flow for liquid 1}}{\text{Rate of flow for liquid 2}} = \frac{\text{Dyn. viscosity of liquid 2}}{\text{Dyn. viscosity of liquid 1}} \times \frac{\text{density of 1}}{\text{density of 2}}$$

since the length and radius of the tube will be the same for both liquids, and the pressure for any given difference in level between the two arms will be proportional to the density of the liquid.

This relationship enables the viscosity of a liquid to be determined in a simple manner. A liquid of known viscosity is allowed to flow through the instrument. The liquid under examination is then treated in an exactly similar manner, and from the times of flow the unknown viscosity can be calculated.

In practice a known volume of the liquid is introduced into the viscometer by filling to definite marks ($C$, $D$), and the instrument is placed in a bath at the specified temperature until the instrument and its contents have acquired that temperature. The liquid is then drawn up to another mark ($A$) and allowed to flow back through the capillary tube. The time taken for a fixed volume of the liquid (indicated by further marks ($A$, $B$,) on the instrument) to flow through the capillary tube is then measured, and the viscosity is calculated by comparison with the standard liquid from the equations—

$$\frac{\text{Time of flow for liquid 1}}{\text{Time of flow for liquid 2}} = \frac{\text{rate of flow for liquid 2}}{\text{rate of flow for liquid 1}}$$

$$= \frac{\text{Kinematic viscosity of liquid 1}}{\text{Kinematic viscosity of liquid 2}}$$

### (7) Ultra-Violet Light Absorption

Ultra-violet light differs from visible light only in its shorter wave-length, to which the human eye does not respond. It is absorbed by many substances, in the same way that visible light is absorbed by coloured substances; and just as the colour of a substance can be a guide to its composition, so the absorption of ultra-violet light can be used to control the composition of suitable substances.

## THE LAWS OF LIGHT ABSORPTION

*Lambert's Law* states that if a parallel beam of monochromatic light is passed through an absorbing substance, the fractional diminution of light intensity caused by a given length of substance is a constant and is independent of the incident light intensity. The fractional diminution in light intensity $= \dfrac{\text{Change in light intensity}}{\text{Original intensity}}$, is (in the symbols of the differential calculus) $\dfrac{dI}{I}$, and leads to the expression

$$\frac{dI}{I} = -Kl$$

where $l$ is the length of absorbing substance through which the light is passed and $K$ is a constant. Mathematical treatment of this expression leads to an exponential equation for the decline in light intensity with distance

$$I = I_0 e^{-\mu l}$$

where the constant $\mu$ is called the *absorption coefficient.*

However, a different constant, called the *extinction coefficient,* is generally used and is defined as "the reciprocal of the thickness which is required to weaken the light intensity to one-tenth of its original value." Symbolically, if the extinction coefficient is represented by $\kappa$ and $I_0$ and $I$ are the original and final intensities after traversing a length of $l$ cm.

$$I = I_0\, 10^{-\kappa l}$$

$\kappa$ is related to $\mu$ by the equation $\mu = 2{\cdot}3026\kappa$.

Lambert's law is strictly true only for monochromatic light; but it is approximately true for white light in many cases.

*Beer's law* of light absorption applies to the case of coloured substances dissolved in colourless (i.e. non-absorbing) solvents, and states that the absorption of the solution is proportional to the concentration of the coloured (absorbing) substance.

It is by no means always followed, but for solutions which agree with the law, the absorption equation above can be re-written

$$I = I_0 10^{-\varepsilon c l}$$

where $\varepsilon$ is the molecular extinction coefficient and $c$ is the concentration of the solute in gramme molecular weights per litre.

*For official purposes* the "extinction coefficient" is referred to the 1 per cent $w/v$ solution (written as $\mathrm{E}_{1\ \mathrm{cm}}^{1\ \mathrm{per\ cent}}$ $x\ \mathrm{m}\mu$, where $x\ \mathrm{m}\mu$ refers to the wave-length of the monochromatic light used in the determination, $1\ \mathrm{m}\mu = 10^{-7}\mathrm{cm}$).

### APPLICATIONS OF LIGHT ABSORPTION

Once the absorption of a compound has been determined for any particular wave-length, this physical property can be used for quantitative analysis, provided that its solutions obey Beer's law. Further checks on the accuracy of any particular determination can be obtained by other determinations involving light of different wave-lengths.

The optical system used for the experimental determination is shown diagrammatically in Fig. 17. For use in the ultra-violet region, it must be constructed of quartz. The light source can be an electric spark between suitable metal electrodes or a gas discharge tube, and the spectra before and after absorption can be recorded on a photographic plate. The intensity of blackening of a photographic plate is not strictly proportional

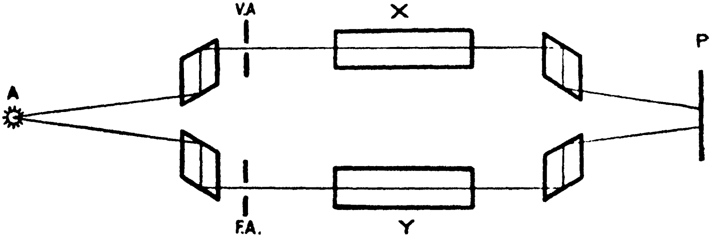


FIG. 17. OPTICAL SYSTEM FOR ULTRA-VIOLET LIGHT ABSORPTION MEASUREMENT

to the quantity of light energy absorbed, but equal light intensities give equal blackening, subject to careful control of the experimental conditions, including the method of development of the plate.

The method of experiment adopted is to divide the incident light source (*A*) into two similar beams, one passing through the solution (*X*) being examined and the other passing directly to the recording plate (*P*). The first beam passes through a slit of fixed aperture (*F.A.*). The intensity of the latter beam is controlled by passing it through a slit of variable aperture (*V.A.*), and a series of photographs is taken with the aperture set at different values. By noticing the aperture at which the two beams give equal blackening of the photographic plate, the extinction of the solution can be calculated. The matching can be effected visually or with the aid of physical instruments using photo-electric cells.

By using another tube (*Y*) containing a standard substance or solution, direct comparisons of the absorption of the unknown and known solutions can be obtained. This may facilitate measurements in many cases. A further possibility, where the relative absorptions are needed over a restricted range of wave-lengths, is to record the intensities photoelectrically, thus saving the time required for plate development and examination.

## CHEMICAL METHODS OF QUANTITATIVE ASSAY

The chemical composition of a substance may be determined quantitatively using the standard methods of gravimetric, volumetric, or gasometric analysis. In recent years, new techniques of chemical analysis have been developed, some of them including the use of physical instruments. These techniques supplement the standard methods but do not supplant them. In the General Notices of the *British Pharmacopœia* the following paragraph is inserted—

"The Assays described are the official methods upon which the standards of the Pharmacopœia depend. The analyst is not precluded from employing an alternative method in any instance if he is satisfied that the method which he uses will give the same result as the official method. In suitable instances, methods of micro-analysis, if of equivalent accuracy, may be substituted for the tests and assays described. In the event of doubt or dispute, the methods of analyses of the Pharmacopœia are alone authoritative."

## Gravimetric Analysis

In this method a known quantity of the substance to be analysed is converted without loss into some other substance of definite composition. The quantity of this substance formed is determined by *weighing* it. From the chemical composition of the product and its relationship with that of the original substance, the composition of the sample under analysis can be calculated.

In most cases the analysis is carried out by the precipitation of an insoluble compound, which is collected, dried, ignited (when necessary), and weighed. The precipitate can be collected on a filter-paper which leaves a known weight of ash when ignited, or in a Gooch crucible. A Gooch crucible is a crucible with a perforated bottom, over which a mat of asbestos fibres is placed to act as a filter or a similar crucible into which is incorporated a sintered glass filter. The Gooch crucible is dried and weighed empty, and again when it contains the precipitate.

The following inorganic substances are assayed officially by gravimetric methods—

(1) By conversion to barium sulphate, Sodium Sulphate (p. 179);

(2) By conversion to metal oxide, (*a*) Alum (p. 262), (*b*) Solution of Ferric Chloride (p. 295);

(3) By conversion to metal phosphate, Precipitated Bismuth and some other bismuth compounds and preparations (p. 217);

(4) By conversion to metal pyrophosphate, Magnesium Sulphate, and Trisilicate (p. 253);

(5) By conversion to metal sulphide, Oleated Mercury (p. 282);

(6) By conversion to metal sulphate, (*a*) Calcium in Compound Syrup of Ferrous Phosphate (p. 257), (*b*) Sodium in Iodoxyl (p. 569);

(7) By conversion to metal chromate, Lead Acetate (p. 267);

(8) By conversion to metal, Gold in Sodium Aurothio-Malate (p. 273);

(9) By conversion to silica, Magnesium Trisilicate (p. 237).

Some alkaloidal preparations and certain other organic substances are also assayed by gravimetric methods.

*The ash content* of a drug is determined by weighing the residue after the ignition, until free from carbon, of a weighed quantity. In some cases, the residue is then extracted with water or dilute hydrochloric acid to distinguish between the soluble and the insoluble fractions of the ash. In other cases the ash is treated with sulphuric acid and weighed as sulphated ash.

*The moisture content* of a substance is determined by measuring the loss of weight on drying. If the substance is stable to heat, it is dried by the application of heat. The temperature of drying must be such that all the water can be removed from the sample within a convenient interval of time without decomposition of the substance. Alternatively, the drying can be effected by leaving for a suitable time in contact with a desiccating agent. In some cases the official composition of a substance is referred to the dried substance. Values obtained by working with the undried sample must be corrected for its moisture content.

*The alcohol-soluble and water-soluble extractives* are determined by standing the drug with the solvent, filtering, removing the solvent from the filtrate and weighing the residue.

## Volumetric Analysis

This form of analysis is based on reactions taking place in solution. A *standard solution* of a known concentration of a reagent is prepared and titrated against a solution of the substance being analysed. From the volumes* of the two solutions which react together, the composition of the sample under examination can be calculated.

In many titrations the solutions which react together are colourless or do not change perceptibly at the point where the reaction is complete. In these cases an indicator must be added which causes an alteration in the appearance of the solution at the *end-point* of the titration. (The theory of indicators for acid-alkali titrations is given on p. 48.)

The concentration of the standard solution is usually referred to that of a normal solution of the particular substance. A *normal solution* of any substance contains 1 gramme-equivalent weight of the substance in 1 litre of solution. The *equivalent weight of an acid* is that weight which contains 1 gramme-atom of hydrogen replaceable by a metal.

---

* Volumes are expressed officially in terms of the millilitre.

The *equivalent weight of a base* is that weight which combines with one equivalent weight of an acid, while the *equivalent weight of a salt* is that weight which is formed by the reaction of one equivalent weight of the corresponding acid with one equivalent weight of the corresponding base.

*Hydrochloric Acid* ($HCl$). 36·47 g contain 1 gramme-atom of hydrogen replaceable by a metal. The equivalent weight equals 36·47 g.

*Sulphuric Acid* ($H_2SO_4$). 98·08 g contain 2 gramme-atoms of hydrogen replaceable by a metal. The equivalent weight equals 98·08/2 = 49·04 g.

*Sodium Hydroxide.* 40·01 g of sodium hydroxide combine with that weight of hydrochloric acid (36·47 g) which contains 1 gramme-atom of replaceable hydrogen. The equivalent weight of sodium hydroxide is 40·01 g.

*Sodium Chloride.* 58·45 g of sodium chloride are formed by the union of one equivalent weight of hydrochloric acid (36·47 g) with one equivalent weight of sodium hydroxide (40·01 g). The equivalent weight of sodium chloride is 58·45 g.

$$NaOH + HCl = NaCl + H_2O$$

*The equivalent weight of an oxidizing agent* is that weight of the substance which yields 8 g of oxygen available for oxidizing purposes, while *the equivalent weight of a reducing agent* is that weight which combines with 8 g of oxygen.

POTASSIUM PERMANGANATE. 316·0 g of potassium permanganate yield 80 g of oxygen available for oxidizing purposes. The equivalent weight is therefore 31·60 g.

$$2KMnO_4 + 3H_2SO_4 = K_2SO_4 + 2MnSO_4 + 3H_2O + 5O$$

IODINE. 253·8 g of iodine yield 16 g of oxygen available for oxidizing purposes. The equivalent weight of iodine is 126·9 g.

$$H_2O + I_2 = 2HI + O$$

SODIUM THIOSULPHATE. 2 × 248·2 g of crystalline sodium thiosulphate ($Na_2S_2O_3, 5H_2O$) react with the weight of iodine (2 × 126·9 g) which is equivalent to 16 g of oxygen. The equivalent weight of crystalline sodium thiosulphate is therefore 248·2 g.

$$2Na_2S_2O_3 + I_2 = 2NaI + Na_2S_4O_6$$

Some substances react in more than one way, and may have more than one value of the equivalent weight depending on the reaction. In those cases where ambiguity may arise, the standard solution can be referred to the molar solution. A *molar solution* of a substance is a solution which contains

1 gramme-molecular weight of the substance in 1 litre of the solution.

The concentrations of standard solutions of potassium iodate are officially given in terms of molarity; for while as an oxidizing agent the equivalent weight of potassium iodate is one-sixth of its molecular weight, one molecule of potassium iodate reacts with two molecules of potassium iodide in the presence of hydrochloric acid to form iodine monochloride.

$$KIO_3 = KI + 3O$$
$$KIO_3 + 2KI + 6HCl = 3KCl + 3ICl + 3H_2O$$

Further confusion may arise as the equivalent weight of potassium iodate, when considered as a salt of a monobasic acid, is equal to its molecular weight.

## Assays of Official Substances

Volumetric methods used in the assays of official substances may be classified into certain main groups. Special individual methods and adaptations are referred to under the particular substance concerned.

### (1) ACID-ALKALI METHODS

(*a*) *Direct Titration*. Practically all the soluble official acids and acid salts are assayed by direct titration with a standard solution of a soluble alkali, using a suitable indicator. Soluble non-volatile alkaline substances and the alkali metal salts of weak inorganic acids are assayed similarly by direct titration with a standard acid solution. Acid or alkaline substances which are not very soluble in water but dissolve readily in presence of a neutral substance [e.g. Benzoic Acid (p. 522) Calcium Hydroxide (p. 254)] are also assayed by direct titration.

(*b*) *Back Titration*. Alkaline substances which are volatile or insoluble in water can be assayed by dissolving in excess of a standard acid solution, the excess acid being determined by titration with standard alkali. Substances which are hydrolyzed by alkalis into acids [e.g. Chloral Hydrate (p. 378)] can be assayed by reaction with excess of a standard solution of an alkali, the excess being determined by titration with a standard acid. When alkali may be lost by side-reactions during the determination [e.g. Acetylsalicylic Acid (p. 527)], the loss is allowed for by carrying out a blank determination in the absence of the substance to be analysed.

Certain other substances [e.g. Ammoniated Mercury (p. 280), Potassium Nitrate (p. 199), Potassium Citrate (p. 418)] are assayed by direct or back titrations with acids or alkalis, after they have been converted to other substances by various chemical reactions.

### (2) OXIDATION-REDUCTION METHODS

*Potassium permanganate* in sulphuric acid solution can be used for the determination of most reducing agents which do not contain chlorides or organic matter, e.g. Ferrous Sulphate (p. 295), Sodium Nitrite (p. 196), Hydrogen Peroxide (p. 151), and calcium compounds (p. 257). It has the advantage of not requiring any added indicator.

*Potassium dichromate* can be used for the determination of reducing agents, in the presence of chlorides and certain organic substances, but it is no longer employed for any official assay process.

*Iodine* can be used for the determination of reducing agents. Arsenious (p. 212) and antimonious (p. 214) compounds are officially assayed in this way. Except in strongly acid solutions, starch solution may be added to assist the detection of the end-point. Starch solution gives a deep blue coloured compound with iodine.

Oxidizing agents are usually assayed officially by taking advantage of the fact that they liberate iodine from an acidified solution of an iodide. The iodine can be titrated with *sodium thiosulphate* solution.

Some substances which react with iodine are assayed by adding excess of a standard solution of iodine and titrating the excess with standard solution of sodium thiosulphate (cf. the chlorides of mercury, p. 279, 280).

*Titanous chloride* (p. 287), *potassium iodate* (p. 166), *iodine monochloride* (p. 293), *bromine* (p. 515), *ceric sulphate* and *sodium nitrite* (p. 509), are also used as official volumetric reagents.

### (3) PRECIPITATION REACTIONS

The reaction of two soluble salts to form an insoluble substance can be used as the basis of quantitative methods of analysis provided the point can be determined at which the two salts have completely reacted together. For reactions of silver nitrate with soluble halides there are two methods used officially for the determination of the end-point.

(*a*) For titrations in neutral solution (e.g. as in the assay of sodium chloride) potassium chromate is used as the indicator as red silver chromate is formed as soon as the silver nitrate has been added in excess (cf. page 56).

(*b*) For titrations in nitric acid solution, excess silver nitrate is added, and the excess determined by titration with a standard solution of ammonium thiocyanate. The indicator used is ferric alum solution, the red colour due to ferric thiocyanate appearing as soon as excess ammonium thiocyanate is present.

$$NH_4CNS + AgNO_3 = NH_4NO_3 + AgCNS$$
$$Fe_2(SO_4)_3 + 6NH_4CNS = 2Fe(CNS)_3 + 3(NH_4)_2SO_4$$

When this method is used for the determination of chlorides [cf, Ammonium Chloride (p. 158)] it is desirable to filter off the precipitate of silver chloride before proceeding to titrate the excess silver nitrate with ammonium thiocyanate. Otherwise, an inaccurate and indefinite end-point will be obtained owing to the reaction of silver chloride with ammonium thiocyanate, since silver chloride is more soluble than silver thiocyanate.

$$AgCl + NH_4CNS = AgCNS + NH_4Cl$$

As silver bromide and iodide are less soluble than silver thiocyanate, bromides and iodides can be titrated directly without removing the precipitated silver halide. Organic halogen compounds can be determined by this method after the halogen has been converted into the ionizable form.

Mercuric salts react with ammonium thiocyanate in a similar manner to the silver salts, and this reaction is used for the determination of certain mercury compounds and preparations (p. 283).

## Gasometric Analysis

This is based on measurements of gas volumes, e.g. the volume of a gas evolved as the result of some chemical action on the substance to be analysed or the changes in the volume of a gas produced by reacting with substances absorbing a possible constituent. Gasometric methods are used officially for the assays of organic nitrites (p. 196) and some of the official gases (e.g. Oxygen, Carbon Dioxide, Ethylene).

## Colorimetric Analysis

Based on reactions leading to the formation of coloured substances, either in solution or as colloidal precipitates, this method is extensively used for detection and determination of traces of substances, and forms the basis for many official limit tests, including those for lead and iron. The colour developed from the sample is compared with that from a known weight of the substance being tested for.

Colorimetric analysis is also used for the assay of morphine in Camphorated Tincture of Opium and of glyceryl trinitrate in Tablets of Glyceryl Trinitrate (p. 396). In the latter case the relative intensity of the colours developed in the sample and standard solutions is measured directly with a colorimeter (p. 127), and the ratio of the colour intensities gives the ratio of the concentrations of nitrate. From this ratio the weight of glyceryl trinitrate in the tablets can be computed. The assays of digoxin in Tablets of Digoxin and of stilboestrol in Tablets of Stilboestrol are carried out in a similar manner, and ergotoxine is determined in Ergot by a colorimetric method.

## Fluorometric Analysis

This is based on reactions leading to the formation of substances which fluoresce (i.e. emit visible light) under the stimulation of ultra-violet light. It is officially applied in the assay of Aneurine Hydrochloride which forms a U.V. fluorescent substance with potassium ferricyanide. The intensity of the fluorescence produced from the sample is adjusted (by taking various amounts of it) until it equals the intensity from a standard solution of aneurine hydrochloride. Thus the percentage of aneurine hydrochloride in the sample is determined.

## Chromatographic Analysis

Chromatography is a method of analysis which enables a mixture of substances to be separated into its components and it can often be used when other methods of separation fail owing to the close similarity of the physical and chemical properties of the substances concerned. It was originally used to separate mixtures of coloured substances such as the various constituents of chlorophyll extracts from plants and the success of the separation was followed by direct observation of the whereabouts of the different colours and the name "chromatography" was devised accordingly. Nowadays, the term is applied to the method irrespective of whether coloured or colourless substances are being separated, the effectiveness of the separation of the latter substances being followed by physical tests (e.g. U.V. fluorescence) or chemical tests (e.g. reactions with indicators) which reveal the whereabouts of the individual components.

The typical apparatus for chromatographic analysis is a vertical glass tube filled with pieces of a solid such as alumina or silica gel (the chromatographic column). The mixture to be separated is placed, usually in solution, at the top of the column and small successive portions of a suitable solvent liquid are then added and allowed to percolate through the material forming the column. Under the treatment and when conditions are favourable, the components of the mixture are found to travel down through the column at different rates and they can be separated into well-spaced zones. The column can then be extruded from the glass tube and cut up into pieces from which the individual substances can be removed by a suitable solvent or by chemical action

An alternative apparatus substitutes filter-paper for the chromatographic column, dipping the upper end in the solvent liquid which percolates continuously down through the pores of the filter-paper. The components are then finally separated by cutting up the filter-paper into pieces containing the various zones.

The principles underlying chromatographic separations are selective adsorption and partition. In adsorption chromatography, e.g. with an alumina column, the substance most strongly adsorbed on the material of the column moves more slowly down the column than the less strongly adsorbed substances, since the latter more readily passes into solution in the solvent liquid. In partition chromatography, e.g. on filter-paper, the base material acts as a reservoir of one liquid (e.g. the filter-paper retains in its pores the solvent with which it was first wetted) and the immiscible solvent liquid moving down the paper extracts from the held liquid the substances according to their partition coefficients. The substance whose partition coefficient most favours transfer to the immiscible solvent is carried most rapidly down the paper.

## TESTS FOR SPECIFIC IMPURITIES

It is theoretically possible for any substance to be adulterated or contaminated by design or accident with any other substance, but no useful purpose is served by a multiplicity of tests for impurities which are, in practice, hardly ever found. The official impurity tests are devised to limit the proportions of those impurities which have been found by experience to occur commonly in the particular substance. The *British Pharmacopœia* states that the official tests are not designed to provide against all possible impurities, and unusual impurities not included in the official tests are not tolerated if rational considerations require that they should not be present.

In general, the most likely impurities may be predicted from a knowledge of the method of preparation of the substance. They arise from such sources as: impurities in the ore or crude material used in the preparation; excess of any reagent used; salts from the water used when the preparation is carried out in aqueous solutions; metallic contamination from steel, copper or brass vessels; and contamination from exposure to the atmosphere (dust or the effects of carbon dioxide or moisture) or changes during storage.

The official impurity tests are not all carried out in the same manner. The sensitivity of some tests and the amount of the impurity tolerated is such that a negative result (indicating the presence of only a small permissible quantity of impurity) can be used as a control. More often a positive result is obtained and the control is effected by comparison with a standard prepared from a prescribed quantity of the impurity which is being tested for. The limit tests for chloride, sulphate, iron, lead, and arsenic, which are applied to a large number of official substances are carried out in this way.

By comparison with a standard, errors due to personal factors in interpretation are avoided. Errors due to personal factors in technique may be minimized by the stipulation of the exact conditions under which the test should be carried out. The composition and quantity of every reagent used in the test, the temperature, and the duration of the test (in those cases where a colour or turbidity may fade or increase on standing) are given in the *British Pharmacopœia.*

## Limit Tests for Chlorides and Sulphates

The limit test for chloride depends on the reaction of a soluble chloride with silver nitrate in nitric acid solution. The small quantity of silver chloride precipitated from a specified weight of the substance forms an opalescence in the solution which is compared with the opalescence obtained from 1 mil of N/100 hydrochloric acid.

The limit test for sulphate depends on the reaction of a soluble sulphate with barium chloride in hydrochloric acid solution. The small quantity of barium sulphate precipitated from a specified weight of the substance forms a turbidity in the solution which is compared with the turbidity obtained from 2·5 mils of N/100 sulphuric acid.

The comparisons are made in Nessler cylinders, after both solutions have been diluted to the same volume. Nessler tubes are colourless glass cylinders with flat bottoms, graduated to hold 50 mils. A pair of tubes is used which should be of the same diameter, so that the heights of the graduations correspond. One tube is used for the standard, and one tube for the test solution, and the solutions are compared. Colours may be matched by looking down the tubes against a white background, while turbidities are compared by observations against a dark background at right angles to the incident light so that the comparison is made by the light scattered by the particles of the suspension.

The stringency of these tests is not varied by altering the amount of impurity added to the standard but by altering the amount of substance taken for the test.

Although the solution containing the substance under test may have exactly the same opalescence or turbidity as the standard solution, it does not follow that exactly equal quantities of the impurity are present in the two solutions owing to specific effects of the substance under test on the solubility and depth of turbidity of the precipitate. Therefore it is not possible to calculate from the experimental turbidities the exact quantity of impurity present in the weight of sample taken, but the tests when applied in the prescribed manner control the amount of impurity present.

## Limit Test for Iron

This test depends on the colour formed by the interaction of thioglycollic acid and a ferrous salt. A known weight of the substance is dissolved in citric acid, thioglycollic acid solution is added, and the colour is compared with a standard colour obtained by the interaction of thioglycollic acid and 0·4 mg of iron. The total iron is controlled by this test as ferric salts are reduced to the ferrous state by the reagents used (cf. p. 451).

### MODIFICATIONS OF LIMIT TESTS

In certain cases it is necessary to modify the procedure for the limit tests for chloride, sulphate, and iron.

Alkaline substances are dissolved in acid, sufficient being prescribed so that the amount of acid required in the normal test remains after the reaction with the alkaline substance.

The soluble impurities present in insoluble substances are extracted with water, the extract being tested for chloride and other impurities. The acids precipitated when solutions of Sodium Benzoate and Sodium Salicylate are acidified are removed by filtration, and the filtrate is used for the tests for chlorides and sulphates.

Deeply coloured substances are decolorized before testing, e.g. Potassium Permanganate is reduced to insoluble hydrated manganese dioxide by boiling with alcohol, and filtering. The filtrate is used for the limit tests for chloride and sulphate.

$$2KMnO_4 + 3C_2H_5OH = 3CH_3.CHO + 2KOH + 2MnO_2 + 2H_2O$$

Reducing substances which would otherwise react with silver nitrate in the chloride limit test are oxidized (e.g. Hypophosphorous Acid is oxidized with nitric acid).

Other special modifications are described under the particular substance concerned.

By the use of a colorimeter or a nephelometer, it is possible to determine the relative intensities of colours or turbidities. The *Duboscq Colorimeter* is shown diagrammatically in Fig. 18.

Light reflected from the mirror *M* passes through the two liquids placed in the tubes *A* and *B*. It is then collected by a pair of prisms *P*, and brought into the eyepiece, whose field of view is divided, one half being illuminated by the light passing through the test solution, the other by light passing through the standard solution.

The method of procedure is to alter the relative lengths of the two solutions through which the light passes until the two parts of the field of view are equal. The ratio of the depths of the colour of the two solutions is then equal to the inverse ratio between the lengths of the two solutions traversed by the light.

The alteration in the length of the solution traversed by the light is carried out by raising or lowering two transparent rods *C* and *D* moving into the liquids in the tubes *A* and *B*. Either rod can be raised or lowered independently of the other.

A *nephelometer* (which is used for the determination of relative turbidities) is constructed on a similar principle, the tubes *A* and *B* having blackened bottoms and transparent sides. Light is directed on the tubes horizontally, and the light scattered vertically by the particles of the suspension is observed through the eyepiece.

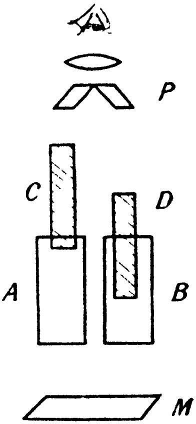


FIG. 18. OPTICAL SYSTEM OF DUBOSQ COLORIMETER

## Limit Test for Lead

The test depends on the formation of a precipitate of lead sulphide by the interaction of lead salts with sodium sulphide in alkaline solution. When only a small quantity of lead is present, the precipitate remains in colloidal suspension, colouring the solution dark-brown. The depth of colour depends on the amount of lead present, and by matching the colour obtained against a standard containing a known quantity of lead, the exact quantity of lead in the sample under test can be determined. The comparison is made in Nessler tubes, both solutions being diluted to the same volume.

The actual procedure is determined by the following considerations—

(1) The substance may contain lead soluble in acid, but insoluble in water. The substance is therefore dissolved in warm dilute acetic acid.*

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* The reagents used in the limit test for lead must be specially purified, and contain less than very small specified quantities of lead. They are distinguished by the letters Pb T.

(2) Lead sulphide is appreciably soluble in dilute acids, and would not precipitate if in small amount. The solution is made alkaline with ammonia,* lead sulphide being much less soluble in alkaline solution (cf. p. 266).

(3) The solution of the substance may be turbid or coloured. The solution can be filtered, or the colour of the standard adjusted to equality by the addition of some neutral colouring matter such as burnt sugar solution.

(4) The substance may contain copper or iron salts as impurities. Potassium cyanide* solution is added to convert the iron and copper compounds to complex cyanides, in accordance with the equations—

$$6KCN + FeSO_4 = K_4Fe(CN)_6 + K_2SO_4$$

$$4KCN + CuSO_4 = K_2Cu(CN)_4 + K_2SO_4$$

These complex cyanides are stable and the metals are not precipitated from them as sulphides, although they are so precipitated in the absence of potassium cyanide.

(4*a*) The potassium cyanide solution may contain sulphides. Hydrogen peroxide is added to the cyanide to oxidize the sulphides to sulphates. The excess hydrogen peroxide rapidly decomposes in the alkaline solution.

(5) The substance to be tested may have specific effects on the colour of the lead sulphide precipitate (cf. chloride and sulphate limit tests, p. 125). In order to obtain an accurate value of the lead content of the substance, errors arising from these effects must be eliminated. This may be accomplished by adding a small quantity of the substance to be tested to the standard solution (the *auxiliary solution*). The difference between the weight of the substance in the test solution (the *primary solution*) and the weight in the auxiliary solution is the weight of the substance which is being tested for its lead content.

The magnitude of the specific effects on the colour of the precipitate tends to reach a maximum when the concentration of the substance to be tested reaches a certain value. Further addition of the substance above the concentration for the maximum effect has no further influence on the colour of the solution. Hence, if the amount of the substance added to the auxiliary solution is sufficient to reach the maximum effect, the extra amount in the primary solution has no further effect on the colour of the solution. Any difference in colour is then due solely to the difference in the lead contents of the two solutions.

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* The reagents used in the limit test for lead must be specially purified, and contain less than very small specified quantities of lead. They are distinguished by the letters Pb T.

It is possible that the influence of the substance under examination on the colour of the lead sulphide precipitate is exerted in the following manner.

Lead sulphide is formed in this test as a colloidal suspension. The colour of a colloidal suspension depends upon the fineness of the particles (i.e. the degree of dispersion). The size of the particles depends on the magnitude of the electric charges on the particles, which cause the particles to repel one another, and not coalesce. The addition of other substances to the solution modifies the electric charges on the particles and therefore the size of the particles of the colloidal suspension, and therefore the colour of the solution.

(6) For convenience of handling, sodium sulphide* is added to precipitate the lead, instead of hydrogen sulphide. The sodium sulphide solution may be filtered to remove any iron sulphide present as impurity.

(7) The test may be used as a limit test, in which case the prescribed amount of lead is added to the auxiliary solution. Or it is possible to determine the actual lead content of the sample being tested by varying the weight of substance taken or the amount of lead added to the auxiliary solution, until the two solutions match exactly.

The general test is modified in special cases, e.g. Calcium Mandelate and Phosphate which are dissolved by the aid ot ammonium citrate;* antimony compounds, when sodium hydroxide* solution is used instead of ammonia to prevent the precipitation of antimony oxide; iron compounds where most of the iron is removed prior to the test, taking advantage of the solubility of ferric chloride in ether; certain organic compounds where the organic matter has first to be removed (cf. arsenic test on phenolphthalein, p. 133).

Some substances cannot be tested by the general lead limit test owing to interference, and special tests must be used. These are described under the particular substance concerned.

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* Cf. footnote, p. 128.

## Limit Test for Arsenic

The limit test for arsenic depends on the fact that when hydrogen is generated in the presence of arsenic the gas arsine ($AsH_3$) is formed, and escapes with the issuing hydrogen. In the official test (which is a modification of the *Gutzeit test*), the arsine is detected by passing the gas through a filter-paper which has been soaked in a solution of mercuric chloride, pressed, and dried in the dark. The arsine reacts with the mercuric chloride giving a yellow or brown stain.

A specified apparatus is used for the official test. It consists of a wide-mouthed bottle fitted with a rubber stopper, through which a tube passes. Two rubber stoppers held together by a rubber band or spring-clip are placed at the top of the tube. The mercuric chloride paper is placed between the two stoppers, so that the gases passing up the tube are brought into contact with the mercuric chloride paper.

The tube contains a piece of filter-paper which has been soaked in a solution of lead acetate and dried. Near the bottom of the tube a small hole in the side of the tube allows the gases to escape into the tube when the bottom becomes sealed by condensed water (Fig. 19).

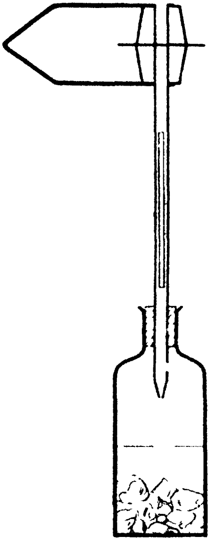

FIG. 19. ARSENIC TEST APPARATUS

The apparatus is designed in such a way that a constant area of the mercuric chloride paper is brought into contact with the issuing gas; and any other way of attaching the mercuric chloride paper is allowed officially provided the whole of the issuing gas passes through a circle of mercuric chloride paper 6·5 mm in diameter, and further that the mercuric chloride paper is protected from sunlight during the test.

## GENERAL METHOD OF TESTING

The *solution to be examined* is first prepared. This solution need not contain the original substance to be tested, but in every case it contains the whole of the arsenic which was present in the original substance. The solution to be examined, which contains 10 mils of *stannated hydrochloric acid** (concentrated hydrochloric acid containing added stannous chloride solution) or its equivalent, is placed in a wide-mouthed bottle with 10 g of zinc.* The tube containing the test papers is placed in position, and the apparatus is allowed to stand in a warm place for forty minutes.

At the same time a similar apparatus containing 10 mils of stannated hydrochloric acid, 50 mils of water, a known quantity of arsenic, and 10 g of zinc is set up. After the prescribed time has elapsed, the two stains on the mercuric chloride papers are compared. The relative depths of the two stains indicate whether the sample under test contains more or less arsenic than was added to form the standard stain.

The test can be used as a limit test, in which case the arsenic in the amount of substance stated in the *British Pharmacopœia* should not exceed the equivalent of 0·00001 g $As_2O_3$, and the standard stain is obtained from this quantity of arsenic. Alternatively, the test may be used to determine the exact proportion of arsenic present in the sample. The quantity of arsenic taken in the standard, or the quantity of sample taken for the test are then varied until the two stains are of equal intensity. Colour charts can be prepared by which the quantity of arsenic present in the sample can be found by direct examination of the stain obtained. In all cases, the stains must be compared immediately in daylight as they fade on standing.

## CHEMICAL REACTIONS

The reaction of pure zinc and pure hydrochloric acid is very slow, but on the addition of another (less reactive) metal dissolution takes place owing to the electrolytic action of the "couple" formed by the two metals. When stannous chloride is added to the pure hydrochloric acid, a certain amount of tin is displaced from the solution, and this is deposited on the surface of the zinc, forming a zinc/tin couple.

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* All reagents used in the limit test for arsenic must be specially purified and contain less than very small specified quantities of arsenic. They are distinguished by the letters As T.

$$SnCl_2 + Zn = ZnCl_2 + Sn$$

The hydrogen which is evolved steadily from this couple has a strong reducing power and converts arsenious compounds into arsine.

$$As_2O_3 + 6H_2 = 3H_2O + 2AsH_3$$

In addition the stannous chloride reduces quinquevalent arsenic compounds (arsen*ic* compounds) to arsenious compounds, and thus accelerates the conversion of the total arsenic to arsine.

The lead acetate paper placed in the tube removes hydrogen sulphide present in the gas, which would otherwise stain the mercuric chloride paper owing to the formation of mercuric sulphide. The hydrogen sulphide is derived from easily reduced sulphur compounds present in the solution to be examined, or from sulphur present in the zinc.

### PREPARATION OF SOLUTION TO BE EXAMINED

In many cases, the substance to be tested is simply dissolved in water and stannated hydrochloric acid is added, but in other cases modifications are necessary.

(1) If effervescence takes place during the solution of the substance in acid, or if the reaction with acid occurs with evolution of heat (e.g. Sodium Carbonate, Potassium Hydroxide) there is a risk of loss of arsenic as arsenious chloride is volatile. In these cases the substance is dissolved in *brominated hydrochloric acid** (concentrated hydrochloric acid to which bromine has been added) instead of stannated hydrochloric acid. The bromine oxidizes all the arsenic to the quinquevalent state; arsen*ic* chloride is not volatile, and therefore no loss of arsenic takes place during the solution of the substance. As soon as all has dissolved and the solution is cool, stannous chloride solution* is added. This removes the excess bromine, converts the quinquevalent arsenic back to the tervalent state (so that it may be converted easily into

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* Cf. footnote, p. 131.

arsine by the hydrogen), and also forms a tin/zinc couple by reaction with the zinc then added.

(2) Boric Acid and Borax are dissolved with the aid of Citric Acid.*

(3) Strong oxidizing agents would interfere with the reduction of the arsenic by the hydrogen, and they are therefore destroyed. Nitric Acid and Potassium Nitrate are evaporated with concentrated sulphuric acid,* until all the nitric acid has been removed. Sodium Nitrite is treated similarly, to avoid production of nitrogen oxides. Potassium Chlorate is heated with hydrochloric acid* until all the chlorine has been removed.

(4) Hypophosphorous Acid, which might otherwise be decomposed into phosphine which stains the mercuric chloride paper and is not held back by the lead acetate paper, is first oxidized to phosphate with potassium chlorate,* the excess chlorate being removed as above. Sodium Metabisulphite is similarly dissolved in presence of potassium chlorate, to oxidize it to sulphate and prevent the generation of sulphur dioxide (which may be reduced to hydrogen sulphide).

(5) Solution of Ammonia and Ammonium Bicarbonate are heated with water on a water-bath until most of the ammonia has been removed. This can be done without loss of arsenic as tervalent arsenic compounds are only volatile in acid, not in alkaline, solutions.

(6) Insoluble organic acids (e.g. Acetylsalicylic Acid) are ignited with calcium hydroxide* to destroy the organic matter. There is no loss of arsenic, owing to the alkali present, and the arsenic remains in the residue of calcium carbonate which is dissolved in brominated acid and treated as above.

The salts of insoluble organic acids (e.g. Sodium Benzoate) are ignited directly, and the residue of carbonate is taken up in brominated acid as above.

(7) In some other organic substances (e.g. Phenolphthalein) the organic matter is first destroyed by heating with a mixture of nitric and sulphuric acids.

(8) Insoluble inorganic substances such as Barium Sulphate and Kaolin are diffused in water, and the test applied directly. Sulphur is digested with ammonia. Any arsenious sulphide is dissolved as a thioarsenite, owing to the formation of ammonium sulphides by reaction with the sulphur. The solution is

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* Cf. footnote, p. 131.

filtered, the filtrate evaporated to dryness, and the residue of arsenious sulphide and sulphur is dissolved in calcium hydroxide. The calcium sulphides produced are oxidized by bromine to sulphates to prevent the formation of large quantities of hydrogen sulphide during the test. The arsenic is also oxidized by the bromine, so after most of the excess bromine has been removed by boiling, stannous chloride is added to remove the remaining bromine and reduce the arsenic to the tervalent condition.

(8) *Interference by Metals.* The metals copper, iron, bismuth, and antimony interfere with the *Gutzeit* test for arsenic. Copper and bismuth deposit on the zinc, causing the evolution of hydrogen of a low reducing power insufficient to convert the arsenic rapidly into arsine. Iron, although it does not deposit on the zinc, also causes the evolution of hydrogen of low reducing power. Antimony forms stibine ($SbH_3$) which stains the mercuric chloride paper and is not held back by the lead acetate paper.

In these cases, the whole of the arsenic is removed from the substance and tested apart from it. Advantage is taken of the fact that arsenious chloride is volatile in acid solution. The substance is dissolved in a mixture of water and concentrated hydrochloric acid* (Iron and Precipitated Bismuth are dissolved in presence of potassium chlorate* to prevent loss of arsenic). The arsenic is reduced to the tervalent state, and the solution is distilled. The whole of the arsenic is contained in the first 75 per cent of the distillate, which contains no other metal except in the case of antimony compounds where a second distillation is required to obtain a complete separation. The distillate is examined for arsenic as in the general test. When sulphur compounds are present in the original substance sulphur dioxide may be formed on distillation, and this is removed by brominated acid before proceeding further.

## Other Common Impurity Tests

### RESIDUE ON EVAPORATION OR SUBLIMATION

An official control of the purity of most volatile substances is afforded by the weight of the non-volatile residue which remains after the evaporation or sublimation of the substance.

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* Cf. footnote, p. 131.

### ACIDITY AND ALKALINITY LIMITS

When the amount of acidity or alkalinity tolerated is small, it is controlled by adding a suitable indicator. The colour change of the indicator indicates whether the sample is within or without the specified limits. If a larger amount is allowed, a quantity of acid or alkali is added just sufficient to neutralize the maximum permissible quantity of impurity. From the reaction of the resulting solution to a suitable indicator, it is possible to ascertain whether the impurity is present in excess of the permissible quantity.

### LIMIT OF OXIDIZABLE MATTER

Oxidizable matter is often controlled by boiling for a certain time with a specified quantity of potassium permanganate solution, whose colour should not be discharged completely.

### METALLIC IMPURITIES

In many cases these are controlled by reaction with a soluble sulphide (lead, copper, and zinc) or ammonia (aluminium, iron, and calcium in presence of carbonates or phosphates). Usually no precipitation or darkening should be caused by the addition of these reagents, but if the amount of impurity tolerated is too large to be controlled in this way, the precipitate may be determined gravimetrically (e.g. aluminium and iron may be converted into and weighed as oxides) Traces of calcium may be determined by gravimetric conversion to sulphate. In the alkali metal bicarbonates, carbonates, and hydroxides, the aluminium, iron and calcium (when present), are determined gravimetrically as a mixture of hydroxides and carbonates together with water-insoluble matter.

Impurity tests of less wide application are referred to later under the substances concerned.

## SECTION III

# INORGANIC CHEMISTRY

# CHAPTER VII

# INTRODUCTION

MANY of the impurities which are found in official substances have their origin in the raw materials from which the substance has been prepared. In order to predict the impurities most likely to be present, the foreign substances present in the raw material must be known. The nature of the foreign substances is closely linked to the state in which the raw material occurs in nature, and the rocks with which it is associated.

## THE OCCURRENCE OF THE ELEMENTS

The primary source of all the elements on the Earth's surface are molten masses, composed mainly of silica and various metallic oxides. Rocks formed by the solidification of these molten masses, which have not been altered appreciably since they solidified, are called *igneous rocks*. The elements which make up the greater bulk of igneous rocks are oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium. Together these elements account for 90 per cent of the total bulk of the rocks. Titanium, carbon, hydrogen, phosphorus, manganese, and sulphur also occur widely in small quantities, and these elements constitute all but 0·1 per cent of the remaining rock constituents. The separation of the elements from igneous rocks is only economically possible when they have been concentrated by later alterations.

During the cooling of molten igneous masses, the high melting constituents crystallize first, so that the more volatile constituents accumulate in the molten residue towards the later stages of cooling. The gases which escape through fissures in recently solidified igneous masses contain large quantities of the more volatile compounds of the lighter elements such as fluorine, chlorine, sulphur, boron, and phosphorus. As these gases pass through the fissures they react with the constituents of the rocks through which they pass, and new compounds are formed, which are deposited in the fissures, forming what are known as *vein deposits*. Many metals become concentrated from the body of the igneous mass into the vein deposits by reaction with escaping hydrogen sulphide, so that the vein deposits are economic sources of these metals. The chief ores of tin, lead, zinc, mercury, antimony, and arsenic are found in vein deposits. Such deposits rarely contain but one mineral, and the metals obtained from these ores may contain other metals accompanying them in the deposit. Other minerals found in vein deposits are apatite (p. 201), fluorspar (p. 153), and barytes (p. 258).

When the igneous rocks have become quite cold, they become subjected to the weathering action of wind, water, ice, etc. They become broken up by mechanical action, and suffer chemical changes, so that the *sedimentary rocks*, which are deposited by the action of wind, water, or ice, differ from the original igneous rocks very considerably.*

The complex silicates, and aluminosilicates, which are the most important constituents of igneous rocks, are not stable at low temperatures in presence of water and the carbon dioxide of the air. They gradually break down. The soluble constituents are washed out, and after prolonged exposure to weathering agencies, only alumina and silica remain. Clay is a typical sedimentary rock which has been exposed to the prolonged action of water.

As an example of the changes occurring during weathering, the decomposition of potash felspar to form kaolinite may be mentioned. Kaolinite is the chief constituent of china clay.

$$\underset{\text{Potash felspar}}{2KAlSi_3O_8} + 2H_2O + CO_2 = \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + 4SiO_2 + K_2CO_3$$

The iron, magnesium, and calcium are removed from igneous rocks as the water-soluble bicarbonates, and may be carried with the soluble alkali metal salts to the sea. By oxidation and loss of carbon dioxide, the iron is often redeposited as hydrated ferric oxide, while calcium and magnesium may be converted through the metabolism of living organisms into calcium and magnesium carbonates. Deposits of the soluble salts of sodium, potassium, calcium, and magnesium are formed by the evaporation of inland seas. The chief sources of iron, calcium, magnesium, sodium, and potassium compounds are sedimentary deposits.

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* Both igneous and sedimentary rocks may suffer alteration by subsequent exposure to high pressures or high temperatures. Further new chemical compounds may be formed during these changes.

The mineral vein deposits in igneous rocks may also be altered by weathering. The metal sulphides are oxidized to sulphates, which if soluble may be dissolved and reprecipitated as carbonates of the metal. Some of these secondary sedimentary deposits are economic sources of the metal they contain (e.g. some copper ores).

# CHAPTER VIII

# OXYGEN AND HYDROGEN

## OXYGEN

OXYGEN is the most abundant element in the Earth's surface. It occurs uncombined in the atmosphere, while most of the earth's crust is composed of oxides (especially water and silica).

Commercially oxygen is obtained by the fractional distillation of liquid air (p. 183), the product containing up to 99 per cent oxygen. Oxygen is also obtained commercially as a by-product of the electrolytic process of manufacture of sodium (p. 243). It is sold, compressed in steel cylinders, for use in oxy-acetylene welding and as an aid to respiration. In the laboratory, oxygen may be prepared by the action of heat on certain metallic oxides (e.g. mercuric oxide, lead dioxide), or oxygen-containing salts (e.g. potassium chlorate).

$$2HgO = 2Hg + O_2$$

$$2PbO_2 = 2PbO + O_2$$

$$2KClO_3 = 2KCl + 3O_2$$

### Properties of Oxygen

Oxygen is a colourless, odourless gas, sparingly soluble in water. (It is slightly more soluble than nitrogen, so that when water is boiled the gas that is driven off is slightly enriched in oxygen. The respiration of fishes depends on dissolved oxygen.)

Chemically, oxygen is a very reactive element which forms compounds (*oxides*) with all the other elements except the inert gases. Most elements combine directly with oxygen, often with sufficient vigour to burn in the gas. Oxygen was chosen as the standard of equivalent and atomic weights partly because of its wide range of combination. Oxygen is essential to respiration and the life of all higher organisms.

Many oxides dissolve in water. The solutions of many non-metallic oxides (e.g. sulphur oxides) give the reactions of *acids* (i.e. they affect blue litmus and other indicators, and they contain hydrogen which is displaced by reaction with metals). Soluble metallic oxides dissolve in water to give *alkaline* solutions which neutralize acids to form *salts*. Those substances (whether soluble or insoluble) which neutralize acids to form salts are called *bases*. Most lower metallic oxides are bases, but a few are *amphoteric* oxides which behave both as an acid and a base.

Some oxides cannot be classified as acidic, basic, or amphoteric. Water, nitric oxide, and carbon monoxide are neutral oxides; sodium peroxide and barium peroxide are derivatives of hydrogen peroxide; while some other oxides (e.g. red lead) have been regarded as salt-like compounds between two other oxides.

Oxygen combines with some compounds, e.g. nitric oxide.

$$2NO + O_2 = 2NO_2$$

The ease of combination is often increased by the presence of a catalyst, e.g. finely divided platinum in the case of sulphur dioxide.

$$2SO_2 + O_2 = 2SO_3$$

Reactions whereby oxygen is added so *that the proportionate* oxygen content of the substance is increased are called *oxidation reactions*. They can be brought about by direct union with oxygen and also through the action of certain other substances which are called *oxidizing agents* (e.g sulphurous acid can be oxidized to sulphuric acid by warming with nitric acid which is an oxidizing agent).

The term oxidation is extended further to include the addition or the increase of the proportion of other non-metallic or electronegative elements or radicles (p. 187) which take the place of oxygen when forming new compounds, e.g. ferrous chloride is oxidized to ferric chloride, and ferrous oxide is oxidized to ferric oxide.

$$2FeCl_2 + Cl_2 = 2FeCl_3$$
$$4FeO + O_2 = 2Fe_2O_3$$

Similarly, mercurous chloride is oxidized to mercuric chloride, and hydrogen iodide to iodine.

$$Hg_2Cl_2 + Cl_2 = 2HgCl_2$$
$$2HI + O = I_2 + H_2O$$

Oxygen B.P. is assayed by taking advantage of the fact that oxygen is absorbed by the powerfully reducing alkaline solution of pyrogallol (p. 517). The fraction of the gas left unabsorbed after shaking with this solution indicates the proportion of foreign gases (chiefly nitrogen, argon and hydrogen) in the oxygen.

The purity tests include limit tests for acidity and alkalinity using unbuffered methyl red solutions adjusted to a standard *p*H value by adding small quantities of standard acid, a limit test for carbon dioxide depending on the turbidity produced with barium hydroxide solution, and negative tests for halogens with silver nitrate, and for foreign oxidizing substances with starch-iodide.

### Ozone

When oxygen (or air) is subjected to the action of a silent electric discharge a fraction is converted into a more active form of oxygen which is called ozone. This form, which is a gas at ordinary temperatures, can be condensed to a deep blue magnetic liquid (b.p. − 112°C).

The molecule of this form of oxygen contains three oxygen atoms instead of two as in ordinary oxygen. This was shown by measuring the volume change which takes place when ozone is converted into oxygen. As pure ozone could not be obtained, the experiments were carried out on a sample of oxygen containing ozone. A measured volume of the sample was heated to decompose the ozone. The expansion was determined. An equal volume of the sample was shaken with turpentine, which absorbed the ozone. The contraction, which was equal to the volume of ozone present in the sample, was found to be twice the expansion produced in the previous experiment.

Hence, 2 vol. of ozone expand by 1 vol. on conversion to oxygen.

∴ 2 vol. of ozone are converted to 3 vol. of oxygen.

∴ 2 molecules of ozone are converted to 3 molecules of oxygen.

∴ The formula of ozone is $O_3$

$$2O_3 = 3O_2$$

Traces of ozone are present in ordinary air, especially at great heights. (It is sometimes used for purifying stale air, e.g. in underground railways.)

Ozone is unstable, and tends to decompose into oxygen especially on warming or in presence of catalysts. Moist ozone decomposes less readily than dry ozone, so that water acts as an anti-catalyst or stabilizer. The ease with which ozone is decomposed causes it to be a vigorous oxidizing agent, e.g. ozone liberates iodine from potassium iodide, and oxidizes many organic compounds. Rubber cannot be used on apparatus containing ozone, as it is attacked by the gas.

The name *allotropy* is applied to that phenomenon whereby elements (e.g. oxygen) can exist in two different forms. The varieties are described as the *allotropes* or the allotropic forms of the element. In the case of oxygen the difference between the two forms is due to the existence of two molecules containing different numbers of atoms. Allotropy may be found in other elements (such as sulphur) where the molecules of the different forms possess the same number of atoms, but the atoms are arranged differently within the molecules.

## HYDROGEN

Hydrogen occurs in nature mainly in combination with oxygen as water. Practically all organic substances contain hydrogen.

Hydrogen can be obtained from water by reaction with certain metals (e.g. sodium) or by passing steam over red-hot carbon. (The hydrogen needed for the manufacture of ammonia (p. 186) is prepared by this last reaction.)

$$2Na + 2H_2O = 2NaOH + H_2$$
$$C + H_2O = CO + H_2$$

A considerable quantity of hydrogen is also obtained as a by-product in the electrolytic manufacture of sodium hydroxide.

In the laboratory, hydrogen may be prepared by reacting with acids (and in some cases alkalis) on metals.

$$Zn + 2HCl = ZnCl_2 + H_2$$
$$Zn + 2NaOH = Na_2ZnO_2 + H_2$$
$$Sn + 2HCl = SnCl_2 + H_2$$

### Properties of Hydrogen

Hydrogen is the lightest known element. Owing to its lightness, hydrogen is used for inflating balloons and airships. Hydrogen is not easily liquefied (b.p. − 255°C).

Hydrogen is a reactive element. It burns readily in oxygen and air to form water, and reacts vigorously with fluorine and chlorine (more gently with bromine and iodine). Most non-metals combine directly with hydrogen.

$$H_2 + S = H_2S$$
$$3H_2 + N_2 = 2NH_3$$
$$2C + H_2 = C_2H_2$$
$$C + 2H_2 = CH_4$$

Hydrogen also combines with some metals to form metal hydrides (e.g. NaH; $CaH_2$). Metallic palladium absorbs large volumes of hydrogen, a property which is sometimes used in gas analysis. It is not certain that a true compound (palldium hydride) is formed.

Hydrogen has such an avidity for oxygen that it is able to remove that element from many of its compounds, e.g. when hydrogen is passed over heated copper oxide the metal is set free.

$$CuO + H_2 = Cu + H_2O$$

The removal of oxygen from a compound (or the proportional decrease of the oxygen content of a compound by addition of hydrogen or an equivalent metallic atom) is termed *reduction*, and substances (like hydrogen) which cause oxygen to be removed are called *reducing agents*.

The term reduction is extended to include the removal (or proportional decrease) of other atoms or radicles which take the place of oxygen, e.g. ferric chloride is reduced to ferrous chloride by removal of chlorine, just as ferric oxide is reduced to ferrous oxide by removal of oxygen.

$$2FeCl_3 + H_2 = 2FeCl_2 + 2HCl$$

$$Fe_2O_3 + H_2 = 2FeO + H_2O$$

Similarly, nitric acid is reduced to nitric oxide, nitrogen, or ammonia.

$$2HNO_3 + 3H_2 = 2NO + 4H_2O$$

$$2HNO_3 + 5H_2 = N_2 + 6H_2O$$

$$HNO_3 + 4H_2 = NH_3 + 3H_2O$$

Reduction is the converse of oxidation and the two processes take place simultaneously. One substance can be reduced only by the oxidation of another, e.g. when titanous chloride reduces ferric chloride to ferrous chloride, it is oxidized to titanic chloride.

$$TiCl_3 + FeCl_3 = TiCl_4 + FeCl_2$$

The efficiency of hydrogen as a reducing agent is often greatly enhanced when it is freshly liberated (especially in contact with a metal). It is then able to reduce substances which are not normally reduced by hydrogen. Advantage is taken of this increased reducing power of freshly liberated hydrogen in the official limit test for arsenic (p. 131).

### Determination of Hydrogen and Oxygen in Organic Compounds

The hydrogen present in organic compounds is determined by conversion to and weighing as water. There is no satisfactory method by which the oxygen present in an organic compound may be determined. The proportion of oxygen is determined by difference after all the other constituents have been measured.

## COMPOUNDS OF HYDROGEN AND OXYGEN

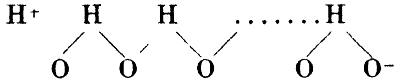
### WATER

Water (which is formed by direct union of oxygen and hydrogen) is found abundantly in nature, both free and in the combined state. Most potable waters contain dissolved salts (e.g. bicarbonates, chlorides, and sulphates). If the water has been in contact with decomposing organic matter, nitrogen compounds (nitrates, nitrites and ammonium salts) may also be present. Soft waters may also contain lead which has been dissolved from pipes, etc. Pure water is obtained from potable water by distillation. Volatile compounds (such as ammonia) can be removed by rejecting the first portion of the distillate, or by pre-heating the water before distillation as in certain special stills. Water dissolves gases from the air, and if it is required to be free from oxygen or carbon dioxide it has to be freshly boiled to remove these gases.

### Properties of Water

The values of the physical constants of water are in many cases taken as standards, e.g. boiling point, melting point, density, and specific heat.

In many ways, the physical properties of water are anomalous compared with other simple substances. Its melting point and boiling point are abnormally high (cf. hydrogen sulphide, m.p. – 83°C, b.p. – 60°C). Instead of decreasing gradually in density as the temperature rises, water has a position of maximum density at 4°C. These facts are explained on the assumption that water consists of a mixture of simple molecules and polymerized molecules. It seems probable that while ordinary ice consists of more or less definite polymerized units, e.g. $(H_2O)_3$, and steam consists of simple molecules ($H_2O$), liquid water contains polymerized units of indefinite though often considerable size, which can be conventionally written as



Water is a unique solvent, especially for acids, bases, and salts owing to its close chemical relationship with these substances.

$$H^+ + OH^- \rightleftharpoons H_2O$$

The solutions of these substances in water conduct electricity owing to ionization. In this respect, water contrasts with organic solvents, such as benzene or chloroform, which are non-ionizing solvents and dissolve non-ionic substances to form non-conducting solutions. Salts, acids and bases are typically insoluble in organic solvents. The solvent action of water is important in nature in the weathering of rocks.

Many substances separate from aqueous solution in crystals which contain combined water (water of crystallization). These crystal hydrates tend to decompose in dry air, and have a definite aqueous vapour pressure, which determines whether the substance is hygroscopic or efflorescent under ordinary conditions (p. 76). Water of crystallization may usually be driven off by heating the crystals to 100°C.

Water also forms loose compounds with substances dissolved in it, more especially with ions most of which are *solvated* (i.e. combined with a rather indefinite amount of water). The hydrogen ion is always solvated, so that it is sometimes written $H_3O^+$.

Chemically, water is a fairly stable substance. Its dissociation is only slight even at high temperatures (10 per cent dissociated at 2,500°C.). Certain metals decompose cold water (e.g. sodium and calcium), others (e.g. magnesium and iron) decompose steam, liberating hydrogen. Chlorine decomposes water slowly in sunlight, liberating oxygen. Water can also be decomposed into its elements by the passage of an electric current. [As pure water is only feebly ionized and is a poor conductor, an acid, base or salt (e.g. sulphuric acid) must be dissolved in it to enable the electrolysis to take place at an appreciable rate.]

The decomposition of certain substances by reaction with water is termed *hydrolysis*. Salts of weak acids or bases are slightly hydrolyzed in aqueous solution (p. 53).

Most non-metallic halogen compounds, and certain organic compounds, are completely hydrolyzed by water.

$$PCl_3 + 3H_2O = H_3PO_3 + 3HCl$$

$$CH_3.COCl + H_2O = CH_3.COOH + HCl$$

Probably owing to its ionic nature, water acts as a very efficient catalyst for many reactions. Complete drying inhibits many reactions which ordinarily take place with great ease, e.g. the reaction of sodium with chlorine, and the reaction of ammonia with hydrogen chloride.

## Detection and Determination of Water

Traces of water may be detected by the conversion of white anhydrous copper sulphate to blue hydrated copper sulphate.

Combined or absorbed water is usually determined by the loss of weight on drying at 100°C. At ordinary temperatures, substances may be dried by standing in a desiccator over sulphuric acid.

## Distilled Water B.P.

Under the official conditions of test, Distilled Water should not give positive reactions for sulphates (with barium chloride), chlorides (with silver nitrate), and lead, copper, and iron (with sodium sulphide). The test for ammonia depends on the brown colour given with Nessler's reagent (p. 281). (Ammonia-free water used as a reagent gives no colour with this reagent.) The colour developed with the Distilled Water is compared with a standard colour prepared from a specified quantity of dilute ammonium chloride solution. The quantity of oxidizable matter is controlled by the stipulation that 1 mil of N/100 potassium permanganate solution should not be decolorized by boiling for ten minutes with 100 mils of the sample of acidified Distilled Water. The quantity of mineral salts present is controlled by the residue on evaporation.

## HYDROGEN PEROXIDE

Hydrogen peroxide is prepared by the action of dilute sulphuric or phosphoric acid on a cold solution of barium or sodium peroxide.

$$BaO_2 + H_2SO_4 = BaSO_4 + H_2O_2$$
$$Na_2O_2 + H_2SO_4 = Na_2SO_4 + H_2O_2$$

After removing the barium or sodium sulphate or phosphate by filtration or crystallization, the hydrogen peroxide is distilled under reduced pressure from the excess acid.

Hydrogen peroxide solutions are not very stable, and commercial samples usually contain stabilizers (e.g. phosphoric acid and acetanilide) to retard their decomposition. The official Solution of Hydrogen Peroxide contains 5 to 7 per cent hydrogen peroxide. When 1 mil of this solution decomposes, about 20 mils of oxygen are evolved (i.e. 20 vol hydrogen peroxide). The quantities of phosphoric acid, and organic substances added as stabilizers are controlled officially by an acidity limit, the residue on evaporation, by extracting with chloroform-ether and, after removing the organic solvent, weighing the residue that has been dissolved in it.

Processes have been developed recently for the manufacture of pure hydrogen peroxide for use in the propulsive mechanism of certain of the newer types of engines. The preparations depend on a distillation process following the electrolytic conversion of sulphuric acid to persulphuric acid (cf. p. 181) and its subsequent decomposition to hydrogen peroxide.

### Properties of Hydrogen Peroxide

Pure hydrogen peroxide is a liquid (b.p. 151°C) which is too unstable for ordinary uses. It is marketed in solution (10 vol, 20 vol, and 100 vol).

Hydrogen peroxide is an unstable substance which breaks down easily into water and oxygen.

$$2H_2O_2 = 2H_2O + O_2$$

The decomposition proceeds more rapidly in alkaline solutions, on warming, and in contact with catalysts, e.g. metallic platinum. The concentration of a hydrogen peroxide solution may be determined by measuring the volume of oxygen evolved during the decomposition. The experiment can be carried out in a nitrometer, and the decomposition accelerated by using a little colloidal platinum as a catalyst.

Hydrogen peroxide is a powerful oxidizing agent. It slowly liberates iodine from potassium iodide, it oxidizes ferrous salts to ferric salts, and oxidizes lead sulphide to sulphate (hence its use to restore old discoloured paintings).

The official method of assay of Solution of Hydrogen Peroxide is based on the reaction of hydrogen peroxide with acidified potassium permanganate solution. The two oxidizing agents reduce one another with the evolution of gaseous oxygen.

$$2KMnO_4 + 3H_2SO_4 = K_2SO_4 + 2MnSO_4 + 3H_2O + 5O$$

$$5H_2O_2 = 5H_2O + 5O$$

$$2KMnO_4 + 3H_2SO_4 + 5H_2O_2$$
$$= K_2SO_4 + 2MnSO_4 + 8H_2O + 5O_2$$

## Derivatives of Hydrogen Peroxide

The formula of hydrogen peroxide is H—O—O—H, with two oxygen atoms united together. Pure hydrogen peroxide is acid in reaction, and metallic peroxides (also containing the —O—O— linkage) are formed when the hydrogen atoms are replaced by metals. Many of the per-acids (but not permanganic acid) are also derivatives of hydrogen peroxide and contain the —O—O— linkage, e.g. percarbonic acid (p. 227) and persulphuric acid (p. 181).

The blue coloured, ether-soluble compound (perchromic acid) formed when hydrogen peroxide reacts with an acid solution of potassium dichromate may contain a similar linkage.

# CHAPTER IX

# THE HALOGENS

THE halogens are a family of four elements, whose chemical and physical properties are similar yet show a gradual change from one element to the next. Fluorine is a pale yellow-green gas [b.p. – 187°C, density 1·14 (at – 200°C)], chlorine is a heavier green gas (b.p. – 34°C, density 1·42), bromine is a dark red heavy liquid (b.p. 59°C, density 3·14), while iodine is a violet solid (m.p. 113°C, b.p. 184°C, density 4·94).

The halogens are chemically reactive and form compounds with most other elements. Their hydrogen compounds are very soluble in water to form strongly acid solutions. The compounds of the halogens with the metals are the corresponding salts. The affinity for hydrogen and the metals diminishes from fluorine to iodine. (Fluorine explodes in hydrogen even at liquid air temperature, and hydrogen fluoride cannot be oxidized to fluorine; a mixture of hydrogen and chlorine explodes at ordinary temperatures if exposed to light, chlorine can be prepared by the action of an oxidizing agent on hydrochloric acid; bromine and hydrogen react steadily without explosion, hydrogen bromide dissociates slightly on heating; the combination of hydrogen and iodine is only partial, and hydrogen iodide is easily dissociated.)

Iodine forms the most stable oxygen containing compounds and chlorine is displaced when potassium chlorate is heated with iodine. (This reaction may be contrasted with the displacement of iodine by chlorine from solutions of iodides.)

$$2KClO_3 + I_2 = 2KIO_3 + Cl_2$$

$$2KI + Cl_2 = 2KCl + I_2$$

$$CdI_2 + Cl_2 = CdCl_2 + I_2$$

**In their compounds with hydrogen and the metals the halogens are usually univalent (although iodine, and to a slight extent also bromine, form salts of higher valency, e.g. $KI_3$; $CsI_5$). The halogens exhibit higher valencies in their**

oxides and oxy-acids as shown in the following table, which indicates the various oxygen compounds of the halogens which have been isolated. Many of these compounds are unstable, and only the hypochlorites and chlorates are of commercial importance.

TABLE VII

| Valency | Fluorine | Chlorine | | Bromine | | Iodine | |
|---|---|---|---|---|---|---|---|
| 1 | $F_2O$ | $Cl_2O$ | $HClO$ | $Br_2O$ | $HBrO$ | | $HIO$ |
| 3 | | | $HClO_2$ | | | | |
| 4 | | $ClO_2$ | | | | | |
| 5 | | | $HClO_3$ | | $HBrO_3$ | $I_2O_5$ | $HIO_3$ |
| (6?) | | $\begin{pmatrix}ClO_3 \text{ or}\\ Cl_2O_6\end{pmatrix}$ | | | | | |
| 7 | | $Cl_2O_7$ | $HClO_4$ | | | | $HIO_4$ |

## FLUORINE

Fluorine occurs chiefly as fluorspar ($CaF_2$) in igneous veins. Cryolite, another mineral containing fluorine, is used in the extraction process of aluminium (p 260).

Owing to the extreme reactivity of fluorine and the stability of its hydrogen compound, the isolation of the element until recently was a difficult matter. It is prepared by electrolysis of a molten mixture of potassium fluoride and anhydrous hydrogen fluoride (i.e $KHF_2$)

Fluorine explodes violently when mixed with hydrogen, and it combines vigorously with many metals It can be handled, however, in vessels of metals whose surfaces become covered with a protective coating of fluoride, and it is increasing in importance industrially on account of the special properties of organic fluorine compounds.

*Hydrogen fluoride* is obtained when concentrated sulphuric acid is heated with a fluoride.

$$CaF_2 + H_2SO_4 \quad CaSO_4 + 2HF$$

Hydrogen fluoride is stored in rubber flasks, as it attacks glass. It is used for etching glass.

$$SiO_2 + 4HF = SiF_4 + 2H_2O$$

When dissolved in water, hydrogen fluoride behaves as a weak acid, which reacts on metals, hydroxides, and oxides to form salts (fluorides).

### Abnormalities of Fluorine

Fluorine differs from the other halogens in several ways. (*a*) The solubilities of many fluorides are abnormal, e.g. calcium fluoride is insoluble, calcium chloride is deliquescent and soluble, silver fluoride is soluble, silver chloride is insoluble. (*b*) Hydrogen fluoride is a much weaker acid than the other hydrogen halides. It also tends to polymerize and form salts (e.g. $KHF_2$) corresponding to the acid $H_2F_2$. (*c*) Hydrogen fluoride forms double salts such as fluorosilicates (p. 232), and fluoroborates (p. 238).

$$SiF_4 + 2HF = H_2SiF_6$$

$$BF_3 + HF = HBF_4$$

(*d*) The fluorides of many non-metals are much less reactive than the corresponding other halides. They are commonly gaseous at ordinary temperatures (e.g. $SF_6$, $PF_5$, $CF_4$).

## CHLORINE

Chlorine is the most important of the four halogen elements. It is not very abundant in igneous rocks (less than 0·1 per cent), but owing to the solubility of the common chlorides, the chlorine in igneous rocks is washed out and concentrated in the sea (which contains about 3 per cent of sodium chloride). On evaporation of sea water, the chlorides are deposited mainly as rock salt, but at later stages of evaporation potassium and magnesium chlorides crystallize. Sodium chloride (obtained by evaporation of sea water, or from salt deposits formed by the drying up of earlier seas) is the chief source of chlorine compounds. The crude salt contains traces of bromides and iodides which are therefore possible impurities in chlorine compounds.

Chlorine is prepared by the electrolysis of brine, the chlorine being evolved at the anode (which must be constructed of graphite to resist attack by the liberated gas). It is a by-product in the electrolytic manufacture of sodium hydroxide. Chlorine (after drying) is stored in iron cylinders.

Formerly, chlorine was manufactured by the oxidation of hydrochloric acid, and it is still prepared in this way in the laboratory.

$$MnO_2 + 4HCl = MnCl_2 + Cl_2 + 2H_2O$$

### Properties of Chlorine

Chlorine is a greenish gas with a characteristic smell. It is easily liquefied to a yellow liquid. Chlorine is fairly soluble in water, but its solution gradually loses strength through chemical reaction.

Chlorine is a reactive element. It combines very readily with hydrogen, the two gases exploding on exposure to light at ordinary temperatures. Chlorine removes hydrogen from various compounds, and thus supports the combustion of certain organic substances, e.g. turpentine.

$$C_{10}H_{16} + 8Cl_2 = 10C + 16HCl$$

Many other elements (non-metals and metals, e.g. phosphorus, copper, and antimony) can be made to burn in chlorine.

The compounds of chlorine with the metals are salts derived from hydrochloric acid.

$$Zn + Cl_2 = ZnCl_2$$

$$ZnO + 2HCl = ZnCl_2 + H_2O$$

$$2Na + Cl_2 = 2NaCl$$

$$NaOH + HCl = NaCl + H_2O$$

The chlorides of non-metals are generally neutral, oily liquids, which are easily hydrolyzed to form a mixture of hydrochloric acid and another acid.

$$PCl_3 + 3H_2O = H_3PO_3 + 3HCl$$

Carbon tetrachloride and nitrogen trichloride differ from the other non-metallic chlorides. They cannot be prepared by direct union of chlorine with carbon or nitrogen, and they are not hydrolyzed by water.

Chlorine forms compounds with the other halogen elements ($FCl$, $F_3Cl$; $BrCl_3$; $ICl$, $ICl_3$).

Chlorine behaves as an oxidizing agent by reason of its strong affinity for hydrogen, e.g. it oxidizes hydrogen sulphide to sulphur.

$$H_2S + Cl_2 = S + 2HCl$$

On standing in sunlight, chlorine water evolves oxygen owing to the combination of chlorine with the hydrogen of the water.

$$2Cl_2 + 2H_2O = 4HCl + O_2$$

Chlorine first reacts with water to form hypochlorous acid. [Chlorine reacts with cold solutions of alkalis in a similar manner (p. 158).] On standing in the sunlight, hypochlorous acid decomposes, evolving oxygen, but in the dark a different reaction takes place and chloric acid is formed. [Chlorine reacts with hot solutions of alkalis to form chlorates (p. 160).]

$$Cl_2 + H_2O = HCl + HClO$$
$$3HClO = HClO_3 + 2HCl$$

Chlorine water is used as an oxidizing agent, and as a bleaching agent (bleaching by oxidation of the colouring matter present). It is considered that the bleaching action of chlorine water is due to its hypochlorous acid content.

## Hydrogen Chloride

Large quantities of hydrogen chloride are prepared by the direct union of hydrogen and chlorine obtained as by-products in the electrolytic manufacture of sodium hydroxide. A comparatively pure product is obtained in this way.

$$H_2 + Cl_2 - 2HCl$$

Hydrogen chloride is also prepared by the action of concentrated sulphuric acid on sodium chloride. The reaction takes place in two stages, the second stage only occurring on raising the temperature after the first has been completed.

$$(1)\ NaCl + H_2SO_4 = NaHSO_4 + HCl$$
$$(2)\ NaCl + NaHSO_4 = Na_2SO_4 + HCl$$

The escaping hydrogen chloride is dissolved in water to form hydrochloric acid, which is often not very pure and contains sulphuric acid, either sulphur dioxide or chlorine, ferric chloride and arsenic. It is purified by immersing copper strips in the diluted acid. The copper combines with the chlorine and arsenic, and reduces the ferric chloride to non-volatile ferrous chloride. On distillation a purer acid is obtained.

The official impurity tests on Hydrochloric Acid for free chlorine, sulphite, bromides and iodides depend on the reactions with cadmium iodide, iodine, and chlorinated lime respectively.

$$CdI_2 + Cl_2 = CdCl_2 + I_2$$
$$SO_2 + 2H_2O + I_2 = H_2SO_4 + 2HI$$
$$2KBr + Cl_2 = 2KCl + Br_2$$

When testing for sulphate, Hydrochloric Acid is neutralized with sodium bicarbonate and evaporated to dryness, as barium sulphate is appreciably soluble in concentrated hydrochloric acid. The residue is dissolved in water and used for the test.

Hydrogen chloride is a gas which fumes strongly in moist air. It is very soluble in water, to form a strongly acid solution. It forms a constant boiling mixture (b.p. 110° C., 20·2 per cent HCl). The dry gas and liquid hydrogen chloride are not acidic and do not react with metals, but the aqueous solution (hydrochloric acid) reacts with many metals, hydrogen being evolved and salts being formed.

$$Zn + 2HCl = ZnCl_2 + H_2$$

Metals which form two series of salts corresponding to different valencies, dissolve in hydrochloric acid to form the lower valency salt (e.g. iron gives ferrous chloride, and tin gives stannous chloride).

$$Fe + 2HCl = FeCl_2 + H_2$$

The higher valency chloride can be obtained by reaction of the metal with chlorine.

$$2Fe + 3Cl_2 = 2FeCl_3$$

Similarly hydrochloric acid reacts readily with alkalis and bases.

Hydrochloric acid is a strong acid (the displacement of hydrogen chloride by sulphuric acid depends not on the relative strengths of the two acids but on the volatility of hydrogen chloride). Most chlorides are soluble in water, those derived from strong bases forming neutral solutions.

*Sodium Chloride* (for purification see p. 243). Sodium chloride is not very soluble in alcohol, but sodium bromide and iodide are appreciably soluble. When sodium chloride is boiled with alcohol, any bromide or iodide present as impurity is dissolved and can be detected by adding chlorine water and chloroform to the alcoholic solution.

*Potassium Chloride* is extracted from the Stassfurt salt deposits (p 248). These two official chlorides are assayed by titration with silver nitrate in neutral solution (p. 121).

*Ammonium Chloride* B.P. is also assayed on its halogen content, but by a silver nitrate—ammonium thiocyanate back titration method. Ammonium Chloride cannot be dried at 100°C without loss, owing to its volatility. The moisture content is determined by drying at ordinary temperatures in a vacuum desiccator over sulphuric acid.

## Oxy-acids of Chlorine

*Hypochlorous Acid* (H—O—Cl). A solution of hypochlorous acid can be prepared by reacting with carbon dioxide on a suspension of bleaching powder in water at 0°C.

Hypochlorous acid is a volatile acid which possesses a characteristic smell. It is a weak acid, which is liberated from its salts even by atmospheric carbon dioxide. (Bleaching powder smells strongly of hypochlorous acid.)

Hypochlorous acid is unstable; on standing in the sunlight it decomposes with evolution of oxygen. In the dark it changes into chloric acid.

$$2HClO = 2HCl + O_2$$
$$3HClO = 2HCl + HClO_3$$

Hypochlorous acid is a powerful oxidizing and bleaching agent.

When chlorine is led into a cold solution of a caustic alkali it reacts to form a mixture of a chloride and a hypochlorite.

$$Cl_2 + 2NaOH = NaCl + NaClO + H_2O$$

*Sodium hypochlorite* solution is manufactured commercially for use as a bleaching agent by electrolysis of brine, allowing the products formed at the electrodes to mix. The solutions thus prepared usually contain excess alkali so that they are not suitable for surgical uses. ✓The official *Surgical Solution of Chlorinated Soda* is prepared by reacting with sodium carbonate on chlorinated lime. Excess alkali is neutralized by the non-irritant and weak boric acid. It is necessary to determine the available chlorine content of the chlorinated lime and adjust the quantities of sodium carbonate and boric acid accordingly.

$$CaOCl_2 + Na_2CO_3 = CaCO_3 + NaCl + NaClO$$

Sodium hypochlorite solution is assayed on its "available chlorine" content. On acidifying, hypochlorous acid is liberated which liberates iodine from potassium iodide. The iodine liberated is determined by titration with sodium thiosulphate.

$$2KI + NaClO + 2CH_3.COOH$$
$$= 2CH_3.COOK + NaCl + H_2O + I_2$$

The "available chlorine" content is calculated from the equation

$$Cl_2 + 2KI = 2KCl + I_2$$

*Bleaching powder* is obtained when trays of slaked lime are exposed for twelve to twenty-four hours in an atmosphere of chlorine. The chlorine is absorbed and a yellowish white powder is formed, which on absorption of water and carbon dioxide from the air smells strongly of hypochlorous acid. Bleaching powder is conveniently represented by the formula $Ca(OCl)Cl, H_2O$, although it is a complex mixture containing a basic calcium hypochlorite $[Ca(OCl)_2, 2Ca(OH)_2]$ and a non-deliquescent basic chloride $[CaCl_2, Ca(OH)_2, H_2O]$.

Bleaching powder is used as an oxidizing and bleaching agent (owing to the hypochlorous acid set free by the action of stronger acids). The "available chlorine" of Chlorinated Lime is officially assayed by reaction with potassium iodide in the presence of acetic acid. The liberated iodine is titrated with standard sodium thiosulphate solution. 4 g of chlorinated lime are triturated with water, transferred to a flask, and diluted to a litre. 100 mils of the milky liquid are taken for the titration.

$$CaOCl_2 + 2CH_3.COOH + 2KI$$
$$= (CH_3.COO)_2Ca + 2KCl + H_2O + I_2$$

The "available chlorine" content is calculated from the equation

$$Cl_2 + 2KI = 2KCl + I_2$$

*Chlorine monoxide* (the anhydride of hypochlorous acid) is obtained as an unstable gas when chlorine is passed over yellow mercuric oxide.

$$2Cl_2 + HgO = HgCl_2 + Cl_2O$$

*Chlorine dioxide* is prepared by the action of concentrated sulphuric acid on potassium chlorate.

$$3KClO_3 + 3H_2SO_4 = 3KHSO_4 + HClO_4 + 2ClO_2 + H_2O$$

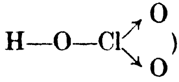
When hydrochloric acid acts on potassium chlorate, a mixture of chlorine and chlorine dioxide is obtained.

$$8KClO_3 + 24HCl = 8KCl + 12H_2O + 9Cl_2 + 6ClO_2$$

*Chlorous acid* ($HClO_2$; $H-O-Cl \rightarrow O$). Chlorine dioxide is hydrolyzed by water to form a mixture of chlorous and chloric acids. The corresponding reaction takes place with alkalies.

$$2ClO_2 + H_2O = HClO_3 + HClO_2$$

$$2ClO_2 + 2KOH = KClO_3 + KClO_2 + H_2O$$

*Chloric Acid* ($HClO_3$;  $H—O—Cl\begin{smallmatrix}\nearrow O\\ \searrow O\end{smallmatrix}$). The chlorates are obtained when chlorine reacts on hot caustic alkali solutions.

$$6KOH + 3Cl_2 = KClO_3 + 5KCl + 3H_2O$$

In this reaction only one-sixth of the potassium hydroxide is converted into potassium chlorate. The waste of potassium compounds is avoided in the electrolytic method of manufacture. Potassium chlorate is obtained when potassium chloride solution is electrolyzed at a temperature about 60°C, and the products of electrolysis are mixed together.

In the official assay of Potassium Chlorate, the substance is reduced by nitrous acid and determined as chloride by the silver nitrate-ammonium thiocyanate method.

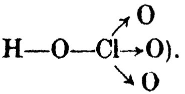
$$KClO_3 + 3HNO_2 = KCl + 3HNO_3$$

Excess of nitrous acid has to be removed before precipitating with silver nitrate, and this is done by adding potassium permanganate and later urea (after the excess of permanganate has been removed with ferrous sulphate).

Potassium chlorate on gentle heating forms potassium perchlorate, but on stronger heating, especially in presence of a catalyst such as manganese dioxide, oxygen is obtained.

$$4KClO_3 = 3KClO_4 + KCl$$

$$2KClO_3 = 2KCl + 3O_2$$

*Perchloric Acid* ($HClO_4$;  $H—O—\overset{\nearrow O}{\underset{\searrow O}{Cl}}\rightarrow O$). Perchlorates are obtained by gently heating chlorates, or by the electrolytic oxidation of chlorates.

$$4KClO_3 = 3KClO_4 + KCl$$
$$KClO_3 + O = KClO_4$$

Perchloric acid is the most stable oxyacid of chlorine, although it and its salts are powerful oxidizing agents. Perchloric acid and its anhydride ($Cl_2O_7$) may be distilled without decomposition, but it becomes dangerously explosive in concentrated solutions in the presence of organic matter. Potassium perchlorate is practically insoluble in alcohol (95 per cent) and potassium salts are quantitatively precipitated by the addition of perchloric acid in the presence of alcohol.

## BROMINE

Traces of bromides are found in deposits formed by evaporation of sea water, and the chief source of bromine compounds is the Stassfurt deposits, which contain traces of magnesium bromide. The bromine is concentrated in the mother liquors after the potassium and magnesium salts have been separated (p. 248). These mother liquors are allowed to flow down a tower up which chlorine is being passed. Bromine is liberated and escapes as vapour at the top of the tower The bromine vapour is condensed, and the traces of uncondensed vapour are absorbed by passing over moist iron filings. The ferrous bromide formed is used to prepare potassium bromide (p. 162).

$$Cl_2 + MgBr_2 = MgCl_2 + Br_2$$

Crude bromine contains chlorine (and there are limit tests for chlorides in all official bromides). The crude bromine is purified by redistillation from a bromide (to hold back the chlorine).

Bromine is a heavy, dark red liquid. It dissolves readily in chloroform, but it is only slightly soluble in water. The aqueous solution is known as *bromine water*. Bromine resembles chlorine in its general chemical properties but does not react quite so vigorously.

### Hydrogen Bromide

This is formed by direct combination of hydrogen and bromine. The reaction proceeds practically to completion at 300° C with a platinum catalyst, but at high temperatures (1,000° C) hydrogen bromide is appreciably dissociated.

$$H_2 + Br_2 \rightleftharpoons 2HBr$$

Hydrogen bromide can also be obtained by distillation of a bromide with concentrated sulphuric acid, but it is more easily oxidized than hydrogen chloride so that considerable quantities of bromine are formed at the same time.

$$2KBr + H_2SO_4 = K_2SO_4 + 2HBr$$
$$2HBr + H_2SO_4 = SO_2 + Br_2 + 2H_2O$$

Hydrogen bromide is conveniently prepared by the hydrolysis of phosphorus tribromide, bromine being dropped on to a mixture of red phosphorus and water.

$$PBr_3 + 3H_2O = H_3PO_3 + 3HBr$$

Hydrogen bromide is a gas resembling hydrogen chloride in its physical properties. It is very soluble in water, forming an acid solution (hydrobromic acid). This solution is conveniently prepared by reaction of bromine with sulphur dioxide in presence of water (the reverse reaction to that which takes place when bromides are heated with sulphuric acid).

$$SO_2 + Br_2 + 2H_2O \qquad 2HBr + H_2SO_4$$

The hydrobromic acid can be separated from the sulphuric acid by distillation.

Hydrobromic acid is a strong acid and reacts readily with metals and bases to form salts (bromides).

*Potassium Bromide* and *Sodium Bromide* are prepared commercially from ferrous bromide by reacting with the corresponding alkali metal carbonate. Iron filings are allowed to react with bromine in the presence of water, after which sodium or potassium carbonate is added. The iron is precipitated as hydroxide and after filtering, the solution is evaporated until the bromide crystallizes. Sodium or potassium bromide can also be obtained by reacting with bromine on a warm solution of sodium or potassium hydroxide. The solution is evaporated to dryness, and the residue is heated with carbon to reduce the bromate.

$$6KOH + 3Br_2 = 5KBr + KBrO_3 + 3H_2O$$
$$2KBrO_3 + 3C = 2KBr + 3CO_2$$

The official test for bromate in Sodium or Potassium Bromide depends on the liberation of bromine when a mixture of a bromide and a bromate is acidified.

$$KBrO_3 + 5KBr + 3H_2SO_4 = 3K_2SO_4 + 3H_2O + 3Br_2$$

The same reaction is used as a source of bromine as a volumetric reagent in certain assay methods (p. 515).

Potassium Bromide B.P. and Sodium Bromide B.P. are officially assayed by silver nitrate—ammonium thiocyanate titration. A correction must be made for the chloride present as determined by the following method.

*Limit Test for Chloride in the Bromides.* The test depends on the oxidation of the bromide to bromine by nitric acid of a concentration such that the chloride is not oxidized. The bromide is dissolved in a mixture of 25 mils of nitric acid and 75 mils of water. The solution is boiled for one minute (longer boiling might result in oxidation of the chloride). During the boiling and for twenty minutes while cooling a current of air is passed through the solution to expel all the bromine. When all the bromine has been removed, the chloride is determined by a silver nitrate titration.

### Oxy-acids of Bromine

The reaction of caustic alkalis with bromine resembles that with chlorine. In the cold hypobromites are formed, but on warming bromates are obtained.

$$2KOH + Br_2 = KBr + KBrO + H_2O$$

$$3KBrO = 2KBr + KBrO_3$$

Sodium hypobromite is used as an oxidizing agent in the determination of urea in urine.

$$CON_2H_4 + 3NaBrO = 3NaBr + CO_2 + 2H_2O + N_2$$

## IODINE

Iodine is present in small quantities in sea water, from which it is concentrated into the substance of seaweeds. From the ash of seaweed (kelp) iodine may be obtained by extracting with water, and after separating the less soluble salts, distilling the mother liquors with concentrated sulphuric acid and manganese dioxide.

$$MnO_2 + 2KI + 2H_2SO_4 = MnSO_4 + K_2SO_4 + 2H_2O + I_2$$

Considerable quantities of iodine are also extracted from the mother liquors from which sodium nitrate (Chile saltpetre) has been extracted. In the Chile saltpetre deposits the iodine is present as iodate, and it is separated by reduction with sodium bisulphite.

$$2NaIO_3 + 5NaHSO_3 = I_2 + 2Na_2SO_4 + 3NaHSO_4 + H_2O$$

Crude iodine contains iodine monochloride (ICl) and monobromide (IBr). Iodine monocyanide (ICN) may also be a dangerous impurity in the iodine obtained from kelp. Iodine is refined by resublimation from potassium iodide.

Iodine monochloride and iodine monocyanide are more soluble than iodine in water. To test for these impurities in Iodine B.P., the sample is triturated with water. After filtering, the solution contains any iodine monochloride or cyanide present, and some iodine. Zinc dust is added which reacts to form zinc chloride, cyanide, and iodide respectively. The cyanide is tested for in one portion of the solution by conversion to Prussian blue (p. 297). The iodide is removed from the other portion of the solution by adding ammonia and silver nitrate, and filtering. (Silver iodide is insoluble in ammonia, but silver chloride is soluble.) The chloride is detected in the filtrate by acidifying with nitric acid.

Iodine occurs as black crystalline plates. Iodine melts at 113°C., but on heating it often sublimes below the melting point. Iodine vapour (which has a purple colour) dissociates into the monatomic form at high temperatures.

$$I_2 \rightleftharpoons 2I$$

Iodine is only slightly soluble in water, but it dissolves readily in carbon disulphide and chloroform to form violet solutions. Small quantities of free iodine may be detected by shaking with chloroform and observing the violet colour of the chloroform layer after it separates (cf. tests for iodides or free chlorine, p. 156; and the volumetric determination of iodides). Iodine dissolves in alcohol, and in aqueous solutions containing potassium iodide to form brown solutions. In these solutions the iodine is probably present in the form of loose chemical compounds, e.g. potassium tri-iodide.

$$KI + I_2 = KI_3$$

Two solutions of iodine in aqueous alcohol are official. The

Strong (10% w/v I) and the Weak (2·5% w/v I) solutions contain 6% Potassium Iodide and 2·5% w/v respectively. There is also an official Aqueous Solution of Iodine containing 5% of Iodine and 10% w/v of Potassium Iodide.

## Properties of Iodine

Iodine combines readily with metals to form iodides. It reacts with hydrogen to form hydrogen iodide, but as the reaction is reversible, an equilibrium state is attained.

$$2HI \rightleftharpoons H_2 + I_2$$

The affinity of hydrogen for iodine is much less than that for chlorine, and consequently iodine is not a powerful oxidizing agent. But sodium thiosulphate is oxidized to sodium tetrathionate by iodine.

$$2Na_2S_2O_3 + I_2 = 2NaI + Na_2S_4O_6$$

The volumetric determination of iodine and many oxidizing agents (which liberate iodine from an acidified solution of potassium iodide) depend on this reaction. The end-point of the reaction is indicated by the disappearance of the brown colour of the free iodine, but the addition of starch solution (with which iodine forms a deep blue coloured compound in the cold) may enable the end-point to be seen more clearly.

Iodine, and the iodine content of its official solutions are assayed officially by sodium thiosulphate titration.

## Hydrogen Iodide

As hydrogen iodide is easily decomposed, and is a strong reducing agent, it cannot be prepared by heating potassium iodide with concentrated sulphuric acid. It can be prepared by the action of water on a mixture of red phosphorus and iodine.

$$PI_3 + 3H_2O = H_3PO_3 + 3HI$$

A dilute solution of hydriodic acid can be obtained by the action of hydrogen sulphide on iodine.

$$H_2S + I_2 \rightleftharpoons S + 2HI$$

The physical properties of hydrogen iodide resemble those of hydrogen chloride and bromide. Its solution in water is strongly acid, and reacts with metals and bases to form salts. Hydriodic acid differs from the other halogen acids in being a powerful reducing agent, so that oxidizing agents liberate iodine from an acidified solution of an iodide.

$$2HI + O = H_2O + I_2$$

$$2KI + H_2SO_4 + O = K_2SO_4 + H_2O + I_2$$

A concentrated solution of hydriodic acid is used as a reducing agent in organic chemistry, e.g. for the reduction of compounds containing hydroxyl groups.

$$ROH + 2HI = RH + I_2 + H_2O$$

The iodides are usually less soluble than the corresponding chlorides and bromides. Many iodides, e.g. mercuric iodide, are coloured. The iodides of the alkali metals (except lithium and sodium) combine with iodine to form polyiodides.

$$KI + I_2 = KI_3$$

Many of the insoluble heavier metal iodides dissolve in a solution of potassium iodide to form complex iodides in which the metal forms part of the complex acid radical (e.g. $K_2HgI_4$, $KBiI_4$, etc.). Some of these complex iodides are valuable analytical reagents.

*Potassium Iodide* and *Sodium Iodide* are prepared from iodine by reactions similar to those used for the preparation of the corresponding bromides (p. 162).

$$FeI_2 + K_2CO_3 + H_2O = Fe(OH)_2 + CO_2 + 2KI$$

$$3I_2 + 6KOH = KIO_3 + 5KI + 3H_2O$$

$$2KIO_3 + 3C = 2KI + 3CO_2$$

The test for iodate in Potassium Iodide B.P. and Sodium Iodide B.P. depends on the liberation of iodine on acidifying. The determination of the potassium iodide content of Aqueous Solution of Iodine is based on the reaction with potassium iodate, which is a strong oxidizing agent, and liberates chlorine from concentrated hydrochloric acid. In the presence of excess potassium iodide, iodine is set free; but, in the presence of excess iodate, iodine monochloride is formed provided that the solution is strongly acid.

$$KIO_3 = KI + 3O$$

$$3O + 6HCl = 3H_2O + 3Cl_2$$

$$2Cl_2 + 4KI = 4KCl + 2I_2$$

$$I_2 + Cl_2 = 2ICl$$

When carrying out the volumetric determination, potassium iodate solution is run into a solution of potassium iodide containing hydrochloric acid. The solution turns brown owing to the liberation of iodine. But if the titration is continued and further quantities of iodate are added, the brown colour gradually fades as the iodine is converted into the pale coloured iodine monochloride. The titration is continued until the iodine has combined completely, as indicated by the disappearance of the violet colour imparted to a globule of chloroform added to the solution. The total reaction is represented by the equation—

$$KIO_3 + 2KI + 6HCl = 3ICl + 3H_2O + 3KCl$$

It follows that 1 gramme-molecule of potassium iodate reacts with 2 gramme-molecules of potassium iodide (2 × 166·0 g), so that 1 litre of M/20 potassium iodate solution reacts on 16·6 g of potassium iodide

During the determination, the iodine originally present in the solution also reacts with the potassium iodate. A correction must be introduced accordingly. The equation for the reaction of potassium iodate with iodine is

$$KIO_3 + 2I_2 + 6HCl = 3H_2O + 5ICl + KCl$$

$$4I = KIO_3$$

It follows that 1 equivalent weight of iodine (which reacts on 10 litres of N/10 sodium thiosulphate solution) reacts on ¼ gramme-molecular weight of potassium iodate, i.e. on 5 litres of M/20 potassium iodate solution. Consequently the action of the iodine on the iodate may be allowed for if half the titration figures of the iodine with N/10 sodium thiosulphate is subtracted from the titration figures with M/20 potassium iodate, assuming that the same volume of the Aqueous Solution of Iodine has been taken for the two titrations.

Potassium iodate titration is also used for the assay of Potassium and Sodium Iodides and for determining the potassium iodide content of the Strong and Weak Solutions of Iodine. The method is modified in these cases by adding potassium cyanide solution before titrating with potassium iodate, and starch solution is used as an internal indicator instead of chloroform as an "immiscible solvent" indicator. Instead of iodine monochloride, iodine monocyanide is formed which does not affect starch.

$$KIO_3 + 2KI + 3KCN + 6HCl = 3ICN + 6KCl + 3H_2O$$

As the iodate method of assay is specific for iodides, and is not affected by the presence of bromides and chlorides, special tests need not be made for the presence of these substances as impurities in iodides.

### Oxy-acids of Iodine

*Hypoiodous acid* (HIO) is relatively unimportant. *Iodic acid* ($HIO_3$) is obtained when iodine is oxidized by nitric acid. It is a solid acidic substance which on heating loses water and forms the anhydride ($I_2O_5$). The iodates are prepared by the action of iodine on hot caustic alkali solutions or by the action of iodine on chlorates.

$$3I_2 + 6KOH = KIO_3 + 5KI + 3H_2O$$
$$I_2 + 2KClO_3 = 2KIO_3 + Cl_2$$

Iodic acid and the iodates are oxidizing agents [cf. the use of iodine pentoxide in the limit test for carbon monoxide in Nitrous Oxide, p. 192) and the use of potassium iodate in the assay of iodides].

$$I_2O_5 + 5CO = 5CO_2 + I_2$$

*Periodates* are formed by the electrolytic oxidation of iodates.

$$KIO_3 + O = KIO_4$$

Complex periodates corresponding to acids $HIO_4$, $xH_2O$ (where $x$ may be as large as 6) are also known.

### Iodine Chlorides

The reaction of chlorine on iodine gives either iodine monochloride (ICl) or iodine trichloride ($ICl_3$), according to the relative proportions of the two halogens.

## Detection and Determination of Halogens in Organic Compounds

Most organic halogen compounds do not give the usual reactions of inorganic halides (e.g. with aqueous silver nitrate solution). The halogens are usually detected and determined by breaking down the organic compound under conditions where the halogen becomes converted to a metallic halide, e.g. if the compound is heated with metallic sodium, the sodium halide salt is formed which can be tested for by the ordinary reactions. Many organic halogen compounds when placed on a copper wire tinge a Bunsen flame green due to the formation of volatile copper halides.

The quantitative determination of halogens in organic compounds may be carried out in four ways—

(1) By heating the substance with concentrated nitric acid and silver nitrate, the halogen is converted to silver halide. This method is used officially in the assay of Iodoform when the excess silver nitrate is determined by a volumetric method.

(2) By ignition with sodium carbonate, the halogen is converted to a sodium salt which can be determined volumetrically This method is adopted officially for the assays of Trichloracetic Acid, Iodophthalein, Injection of Diodone and Chiniofon.

The substance is mixed with sodium carbonate in a small crucible, which is inverted in a large crucible, the junction of the two crucibles being sealed by adding more sodium carbonate. After heating and cooling, the sodium halide is extracted in water and determined by a suitable method. In the case of Trichloracetic Acid the sodium chloride formed during the ignition is determined by the silver nitrate—ammonium thiocyanate method. The sodium iodide obtained from Iodophthalein is determined by titration with potassium iodate.

(3) The organic halide can sometimes be broken down by reaction with a metal and thus converted into halide salts. In the official assay of Iodoxyl, the substance is treated with zinc and the zinc iodide determined by titration with potassium iodate in the presence of potassium cyanide. Sodium is used for the determination of chlorinated compounds in Benzoic Acid and Mandelic Acid.

(4) The bromine in Tribromoethyl Alcohol is rendered reactive towards silver nitrate by a preliminary alkaline hydrolysis.

# CHAPTER X

# SULPHUR

SULPHUR is not a very abundant element (about 0·1 per cent of the earth's crust). The chief source of sulphur compounds is iron pyrites ($FeS_2$) which on roasting in air forms sulphur dioxide.

Native sulphur is found in volcanic districts, notably in Sicily and in Louisiana, U.S.A. The sulphur is melted to separate it from associated earthy matter. (In Louisiana the sulphur deposits are not surface deposits. The sulphur is melted by superheated steam and pumped to the surface in the liquid condition.) Crude sulphur may contain sulphuric acid from its oxidation, and arsenic. These impurities are removed by treatment with ammonia. The sulphur is then redistilled. The first runnings are deposited in the receiver as a solid (flowers of sulphur), afterwards liquid sulphur is collected and cast into sticks (roll sulphur).

## Properties of Sulphur

Sulphur is a brittle, yellow solid which exists in several allotropic forms. The stable form at normal temperatures is soluble in carbon disulphide, and crystallizes in rhombic crystals. It is a non-conductor of electricity. This form of sulphur is stable at temperatures below 96°C, but above this transition temperature a form crystallizing in prismatic needles (monoclinic sulphur) becomes the more stable. Owing to the slow rates of change, rhombic sulphur may be heated to melting (m.p. 112·8°C) without conversion, and monoclinic sulphur may be supercooled to ordinary temperatures.

Other crystalline forms of sulphur have been obtained which have the same molecular weight ($S_8$) as rhombic and monoclinic sulphur. The differences in crystal form are probably due to different arrangements of the sulphur molecules in forming the various crystals.

When sulphur is formed as the result of a chemical reaction (e.g. the action of acids on calcium polysulphides) it is precipitated in a finely divided amorphous state. Precipitated

Sulphur B.P. may be distinguished from the more coarse and crystalline Sublimed Sulphur (flowers of sulphur) by microscopic examination. In some cases the precipitated sulphur may be fine enough to remain in colloidal suspension (colloidal sulphur).

When sulphur is first melted a clear liquid is obtained, but on heating to 160°C the molten sulphur becomes dark and viscous. At higher temperatures, the liquid becomes mobile again. The first clear liquid contains one form of liquid sulphur ($S_\lambda$), the viscous liquid formed at higher temperatures contains another type of liquid sulphur ($S_\mu$). When viscous sulphur is cooled rapidly, a plastic mass of supercooled liquid sulphur (plastic sulphur) is obtained. On standing, this changes slowly into a solid mass, which consists of a mixture of soluble sulphur (corresponding to $S_\lambda$) soluble in carbon disulphide, and insoluble sulphur (corresponding to $S_\mu$). $S_\lambda$ and $S_\mu$ have the same molecular weight ($S_8$), and the different properties of the two forms of liquid sulphur must be caused by different arrangements of the sulphur atoms in forming the two molecules.

Sulphur vapour (whose density corresponds to the formula $S_8$ at low temperatures) undergoes partial dissociation on heating. Dissociation is complete at 780°C.

$$S_8 \rightleftharpoons 4S_2$$

The term *dissociation* is applied to cases of reversible chemical decomposition of a substance into simpler substances. *Association* is applied to cases of reversible combination of two or more molecules of a simple substance to form a single molecule of a more complex substance. It is a special case of polymerization (p. 336).

The changes in the composition of sulphur vapour illustrate dissociation and association.

### CHEMICAL PROPERTIES OF SULPHUR

**Sulphur is a reactive element, which combines readily with oxygen, hydrogen, most other non-metals, and many metals. It does not react with acids, but dissolves in alkalis forming sulphides, thiosulphates and polysulphides. In its compounds with hydrogen and the metals sulphur is bivalent, but in its oxides and related compounds sulphur is quadrivalent or sexavalent.**

## Hydrogen Sulphide

The simplest compound of hydrogen and sulphur (hydrogen sulphide, sulphuretted hydrogen) is found in various natural waters. It is formed during the decomposition of organic sulphur compounds. It is usually prepared by the action of dilute sulphuric acid on ferrous sulphide (which is formed when metallic iron and sulphur are heated together).

$$Fe + S = FeS$$

$$FeS + H_2SO_4 = FeSO_4 + H_2S$$

A purer product is obtained by the action of hydrochloric acid on antimony sulphide.

$$Sb_2S_3 + 6HCl = 2SbCl_3 + 3H_2S$$

Hydrogen sulphide is a gas with a characteristic smell. It is soluble in water forming a weakly acid solution.

Hydrogen sulphide is not very stable. It decomposes on heating.

$$H_2S = H_2 + S$$

It burns readily in air (forming sulphur or sulphur dioxide according as there is present a deficiency or an excess of oxygen).

$$2H_2S + O_2 = 2H_2O + 2S$$

$$2H_2S + 3O_2 = 2H_2O + 2SO_2$$

An aqueous solution of hydrogen sulphide oxidizes slowly in air depositing sulphur, and being so readily oxidized it behaves as a reducing agent.

Hydrogen sulphide is a dibasic acid, i.e. it contains two atoms of hydrogen which are replaceable by a metal. Salts can therefore be derived from hydrogen sulphide when one or both of the hydrogen atoms are replaced (e.g. KHS; $K_2S$).

Salts which are derived from acids by replacing only part of the acidic hydrogen by metals are termed *acid salts** (e.g. KHS). The salts which are formed when the whole of the acidic hydrogen of an acid is replaced by a metal are termed *normal salts** (e.g. $K_2S$). *Basic salts** are compounds of normal salts with the corresponding base (cf. basic calcium phosphate p. 208).

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* These terms should not be confused with the reaction of the solution of the salt to indicators. Thus, disodium hydrogen phosphate is an acid salt, although the reaction of its solution is practically neutral. The normal salt (trisodium phosphate) is strongly alkaline in solution (p. 206).

Sodium, potassium or ammonium hydrogen sulphide is prepared by passing hydrogen sulphide into a solution of sodium, potassium or ammonium hydroxide until no more is absorbed.

$$KOH + H_2S = KHS + H_2O$$

If to the resulting solution a further quantity of alkali is added equal to that first used, the normal sulphide is obtained.

$$KOH + KHS = K_2S + H_2O$$

Many normal sulphides can be prepared by reaction of a metal with sulphur or hydrogen sulphide.

$$Fe + S = FeS$$

$$Ag + H_2S = AgS + H_2$$

The insoluble sulphides can also be obtained by precipitation from solution with hydrogen sulphide.

$$CuSO_4 + H_2S = CuS + H_2SO_4$$

Hydrogen sulphide is a valuable reagent in qualitative analysis as the metals may be separated by taking advantage of the differences in the solubilities of their sulphides (p. 57). The solubility of arsenic, antimony and tin sulphides in ammonium sulphide solution enables a further separation to be effected.

Many metals can be determined quantitatively by precipitation and weighing as sulphide (e.g. mercury, p. 282), and small quantities of metals may be detected or determined by examination of the colour imparted to the solution by traces of the dark-coloured sulphide precipitates (e.g. lead limit test, p. 127).

### THE POLYSULPHIDES

The solutions of the sulphides of the alkali metals and ammonium readily absorb sulphur and become yellow due to the formation of polysulphides.

$$(NH_4)_2S + nS = (NH_4)_2S_{n+1}$$

When sulphur is dissolved in caustic alkalis, sulphides and sulphites are first formed.

$$3S + 6KOH = 2K_2S + K_2SO_3 + 3H_2O$$

These substances are able to absorb more sulphur to form polysulphides (e.g. $K_2S_2$, $K_2S_3$, $K_2S_4$), and thiosulphates.

$$K_2S + S = K_2S_2$$

$$K_2S + 2S = K_2S_3, \text{ etc.}$$

$$K_2SO_3 + S = K_2S_2O_3$$

When acid is added to the final product, sulphur is precipitated.

$$2K_2S + K_2SO_3 + 6HCl = 6KCl + 3H_2O + 3S$$

(The official Precipitated Sulphur is obtained by acidifying the product obtained when lime reacts on sulphur.)

Hydrogen polysulphides have been prepared ($H_2S_x$, where $x = 2, 3$, or 5) by carefully adding acid to polysulphides of the alkali metals and ammonium. They are easily decomposed into hydrogen sulphide and sulphur.

$$H_2S_2 = H_2S + S$$

## OXYGEN COMPOUNDS OF SULPHUR

Sulphur forms two important oxides, sulphur dioxide ($SO_2$) and sulphur trioxide ($SO_3$), which are the anhydrides of sulphurous acid ($H_2SO_3$) and sulphuric acid ($H_2SO_4$) respectively. Sulphur forms other oxyacids, e.g. hydrosulphurous acid ($H_2S_2O_4$), thiosulphuric acid ($H_2S_2O_3$), the persulphuric acids ($H_2SO_5$ and $H_2S_2O_8$), and the thionic acids ($H_2S_xO_6$ where $x = 2, 3, 4, 5$, or 6). Most of these other acids are unstable and easily decomposed. A third oxide of sulphur ($S_2O_7$, the anhydride of perdisulphuric acid $H_2S_2O_8$) has been prepared.

### Sulphur Dioxide and Sulphurous Acid

Sulphur dioxide is the chief product formed when sulphur is burnt in air. (A little sulphur trioxide is formed at the same time.)

$$S + O_2 = SO_2$$

Commercially, sulphur dioxide is obtained by roasting sulphides (especially iron pyrites) in air.

$$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2$$

The crude gas contains sulphur trioxide, arsenious oxide, and other solids and dusts. These may be separated by filtration, washing, and settling.

In the laboratory, sulphur dioxide is prepared either by reducing concentrated sulphuric acid by heating it with copper, or by the action of a dilute acid on a sulphite.

$$Cu + 2H_2SO_4 = CuSO_4 + SO_2 + 2H_2O$$

$$Na_2SO_3 + 2HCl = 2NaCl + SO_2 + H_2O$$

Sulphur dioxide is a strong smelling gas, which is easily liquefied (b.p. $-10°C$). It dissolves in water to form a solution which is acid in reaction and probably contains some sulphurous acid.

$$SO_2 + H_2O \rightleftharpoons H_2SO_3$$

Sulphurous acid is a weak dibasic acid which forms acid and normal salts (bisulphites, e.g. $KHSO_3$ and sulphites, e.g. $K_2SO_3$). Metabisulphites derived from the acid $H_2S_2O_5$ (i.e. $2SO_2, H_2O$) are also obtainable. When sulphur dioxide is passed into sodium hydroxide solution until it is saturated, sodium bisulphite is formed. On evaporation, this substance loses water and sodium metabisulphite is obtained.

$$NaOH + SO_2 = NaHSO_3$$

$$2NaHSO_3 = H_2O + Na_2S_2O_5$$

Normal sodium sulphite is prepared from the bisulphite by reacting with another equivalent of sodium hydroxide.

$$NaHSO_3 + NaOH = Na_2SO_3 + H_2O$$

Normal sodium sulphite is prepared commercially by the reaction of sulphur dioxide on sodium carbonate.

$$Na_2CO_3 + SO_2 = Na_2SO_3 + CO_2$$

Sulphur dioxide is easily oxidized to sulphur trioxide. In aqueous solution it is a strong reducing agent. It reduces ferric salts to the ferrous state. It decolorizes potassium permanganate, and reacts with chlorine. Sulphur dioxide reacts with metallic peroxides and dioxides to form sulphates. The corresponding reaction with hydrogen peroxide is utilized in the official control of sulphur dioxide in Liquid Glucose (p. 465).

$$Fe_2(SO_4)_3 + 2H_2O + SO_2 = 2FeSO_4 + 2H_2SO_4$$

$$H_2SO_3 + H_2O + Cl_2 = H_2SO_4 + 2HCl$$

$$PbO_2 + SO_2 = PbSO_4$$

$$Na_2O_2 + SO_2 = Na_2SO_4$$

The use of sulphur dioxide as a bleaching agent, and the method of determination of sulphites (including Sodium Metabisulphite) by reaction in acid solution with a standard solution of iodine, depend on the reducing action of sulphur dioxide.

$$Na_2SO_3 + I_2 + H_2O = Na_2SO_4 + 2HI$$

$$Na_2S_2O_5 + 2I_2 + 3H_2O = Na_2SO_4 + H_2SO_4 + 4HI$$

Sulphur dioxide combines directly with chlorine and with oxygen in the presence of a catalyst.

$$SO_2 + Cl_2 = \underset{\text{Sulphuryl chloride}}{SO_2Cl_2}$$

$$2SO_2 + O_2 \rightarrow 2SO_3$$

## CONSTITUTION OF SULPHUROUS ACID

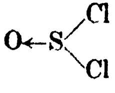
When phosphorus pentachloride reacts on sulphur dioxide, thionyl chloride is obtained.

$$SO_2 + PCl_5 = \underset{\text{Thionyl chloride}}{SOCl_2} + POCl_3$$

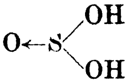
This substance behaves as the acid chloride corresponding to sulphurous acid, which is formed when thionyl chloride is hydrolyzed. An *acid chloride* is obtained from an acid by replacement of the hydroxyl group by a chlorine atom (cf. p. 392).

$$SOCl_2 + 2H_2O = 2HCl + H_2SO_3$$

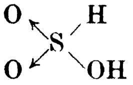
Thionyl chloride must be represented by the formula



corresponding to the formula for sulphurous acid



Nevertheless, it has been suggested that some organic derivatives of sulphurous acid correspond to the sexavalent sulphur formula



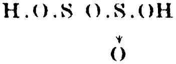
It is possible that sulphurous acid should be represented by both formulae (cf. tautomerism, p. 471).

### HYDROSULPHUROUS ACID

Sodium hydrosulphite is used commercially as a powerful reducing agent. It is obtained either by the electrolytic reduction of sodium bisulphite, or by dissolving zinc in sodium bisulphite solution.

$$Zn + 4NaHSO_3 = ZnSO_3 + Na_2SO_3 + Na_2S_2O_4 + 2H_2O$$

The formula of hydrosulphurous acid is probably



$$H.O.S\ O.\underset{\overset{\downarrow}{O}}{S}.OH$$

## Sulphur Trioxide and Sulphuric Acid

Sulphur trioxide is prepared by the reaction of sulphur dioxide with oxygen in the presence of a catalyst.

$$2SO_2 + O_2 = 2SO_3$$

In the contact process for the manufacture of sulphuric acid, the combination is accelerated by contact with a solid catalyst (e.g. finely divided platinum). This catalyst easily becomes poisoned (p. 91) and rendered inactive by impurities (especially arsenic) present in the sulphur dioxide, and the gases obtained by burning pyrites must be purified very carefully before passing over the catalyst.

The sulphur trioxide formed by passing the mixed gases over the catalyst dissolves very slowly in water. It is therefore absorbed in sulphuric acid to form fuming sulphuric acid ($H_2S_2O_7$; oleum), which is afterwards diluted according to requirements. The sulphuric acid obtained by this process is comparatively pure, owing to the preliminary purification of the gases which is necessary to prevent poisoning of the catalyst.

The formation of sulphur trioxide is reversible, an equilibrium state being obtained.

$$2SO_2 + O_2 \rightleftharpoons 2SO_3$$

As the forward reaction is exothermic, the proportion of sulphur trioxide in the equilibrium mixture diminishes as the temperature rises, so that a larger conversion of sulphur dioxide to trioxide is obtained by working at as low a temperature as possible. But the rate of reaction is less at lower temperatures so that equilibrium may not be attained during the time the gases remain in contact with the catalyst. In practice, a temperature is adopted compromising between these opposing factors. The more efficient the catalyst, the lower is the temperature at which it is possible to work, and thus the greater the quantity of sulphur dioxide converted. Using platinum as catalyst at a temperature of 400–450° C, about 90 per cent may be converted.

In the lead chamber process for the manufacture of sulphuric acid, the oxidation of sulphur dioxide by air is carried out with the help of nitrogen oxides, which act as oxygen carriers (various intermediate substances may be formed during the conversion).

$$H_2O + SO_2 + NO_2 = H_2SO_4 + NO$$
$$2NO + O_2 = 2NO_2$$

The preparation is carried out in lead chambers, into which the gases from burning pyrites are led mixed with nitrogen oxides. Water is passed in as steam or as a fine spray, and dilute sulphuric acid accumulates at the bottom of the chamber. The nitrogen oxides are recovered from the gases escaping from the chamber and returned to the chamber.

Lead chamber sulphuric acid is concentrated by evaporation. It is not as pure a substance as that made by the contact process. It may contain lead, nitrates, and impurities derived from the burning pyrites.

### PROPERTIES OF SULPHURIC ACID

Sulphuric acid is an oily liquid which is very hygroscopic. Its affinity for water enables it to be used as a drying agent, and to assist in chemical reactions involving the removal of water [e.g. nitration (p. 491), esterification (p. 350)]. It is very corrosive (partly due to its dehydrating action on organic matter). Sulphuric acid forms various hydrates with water; $H_2SO_4$, $H_2O$; $H_2SO_4$, $2H_2O$; and $H_2SO_4$, $4H_2O$ have been isolated in the crystalline state. Sulphuric acid and water form a maximum boiling point mixture (b.p. 330°C, 98·8% $H_2SO_4$).

Sulphuric acid when diluted with water forms a strongly acid solution. On account of its high boiling point, sulphuric acid will displace more volatile acids from their salts.

As sulphuric acid is a dibasic acid it forms acid and normal sulphates, most of which are soluble in water (barium, strontium, and lead sulphates are insoluble).

*Sodium Sulphate* is obtained when sodium chloride is heated with concentrated sulphuric acid. It can also be obtained by double decomposition from magnesium sulphate. It is purified by recrystallization from water.

$$2NaCl + MgSO_4 = MgCl_2 + Na_2SO_4$$

Sodium sulphate crystallizes from water as a decahydrate ($Na_2SO_4$, $10H_2O$), which forms efflorescent crystals. Sodium sulphate readily forms supersaturated solutions, which may deposit crystals of a heptahydrate ($Na_2SO_4$, $7H_2O$).

*Sodium Acid Sulphate* is obtained in the manufacture of nitric acid.

$$NaNO_3 + H_2SO_4 = NaHSO_4 + HNO_3$$

It is used industrially as a substitute for sulphuric acid.

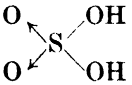
*Potassium Sulphate* is obtained by recrystallization of the naturally occurring substance, kainite ($K_2SO_4$, $MgSO_4$, $MgCl_2$, $6H_2O$), or from potassium chloride by heating with concentrated sulphuric acid.

Other metal sulphates may be obtained by reacting with dilute sulphuric acid on the metal, oxide, or carbonate, or, in the case of the insoluble sulphates, by precipitation.

*Determination of Sulphate.* Sulphates are determined gravimetrically (as in the official assay of Sodium Sulphate) by precipitation with barium chloride and weighing as barium sulphate.

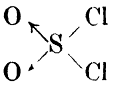
## CONSTITUTION OF SULPHURIC ACID

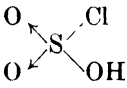
Sulphuric acid is represented by the formula

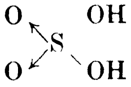


corresponding to the acid chloride (sulphuryl chloride) and the half acid chloride (chlorosulphonic acid) prepared by the reaction of sulphur trioxide on hydrogen chloride.

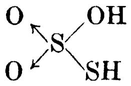
$$SO_3 + HCl = HOSO_2Cl$$


Sulphuryl chloride


Chlorosulphonic acid


Sulphuric acid

*Thiosulphuric Acid* is an acid obtained by replacing one of the oxygen atoms of sulphuric acid by sulphur.


Thiosulphuric acid

The acid is very unstable and breaks down as soon as it is liberated from its salts. When a solution of sodium thiosulphate is acidified, sulphur is precipitated and sulphur dioxide is evolved.

$$Na_2S_2O_3 + 2HCl = 2NaCl + SO_2 + S + H_2O$$

*Sodium Thiosulphate* is obtained by dissolving sulphur in sodium sulphite solution.

$$Na_2SO_3 + S = Na_2S_2O_3$$

Sodium thiosulphate is also obtained from the waste lime used in the purification of coal gas (p. 223), and the alkali waste of the Leblanc process (p. 249). On standing in the air, the sulphur in these products is converted to calcium thiosulphate. Sodium thiosulphate is obtained by treatment of this substance with sodium carbonate.

$$CaS_2O_3 + Na_2CO_3 = Na_2S_2O_3 + CaCO_3$$

Sodium thiosulphate is easily oxidized. When it reacts with iodine, sodium tetrathionate is obtained, a reaction which serves as the basis for the volumetric determination of iodine and oxidizing agents (p. 120).

$$2Na_2S_2O_3 + I_2 = Na_2S_4O_6 + 2NaI$$

Sodium thiosulphate is used in photography to dissolve the unexposed silver halides, and thus obtain a permanent impression (p. 271).

$$AgCl + Na_2S_2O_3 = NaAgS_2O_3 + NaCl$$

*Persulphuric Acids.* The most important persulphuric acid is $H_2S_2O_8$, i.e. $H_2O_2, 2SO_3$ (perdisulphuric acid). The salts of this acid are obtained by electrolysis of solutions of bisulphates.

Persulphuric acid is obtained by electrolyzing a 60 per cent solution of sulphuric acid which contains the acid sulphate ion owing to incomplete dissociation.

$$H_2SO_4 \rightleftharpoons H^+ + HSO_4^-$$

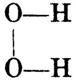
$$2HSO_4 = H_2S_2O_8$$

The persulphates are powerful oxidizing agents. They decompose slowly into hydrogen peroxide in aqueous solution.

$$H_2S_2O_8 + 2H_2O = H_2O_2 + 2H_2SO_4$$

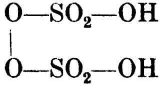
They differ from hydrogen peroxide in being without action on potassium permanganate.

The formulae of per*di*sulphuric acid and per*mono*sulphuric acid ($H_2SO_5$, i.e. $H_2O_2$, $SO_3$) are given below. They are derivatives of hydrogen peroxide.



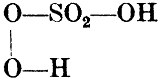
$$\begin{array}{l} O-H \\ | \\ O-H \end{array}$$

Hydrogen peroxide



$$\begin{array}{l} O-SO_2-OH \\ | \\ O-SO_2-OH \end{array}$$

Per*di*sulphuric acid



$$\begin{array}{l} O-SO_2-OH \\ | \\ O-H \end{array}$$

Per*mono*sulphuric acid

*The thionic acids* are represented by the formulae $H_2S_xO_6$ where $x = 2, 3, 4, 5$, or 6. Manganese dithionate is obtained by the reaction of manganese dioxide on sulphur dioxide

$$MnO_2 + 2SO_2 = MnS_2O_6$$

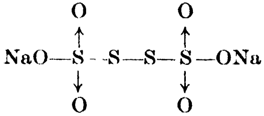
Sodium tetrathionate is obtained by oxidation of sodium thiosulphate with iodine. All the thionic acids are present in the solution obtained when hydrogen sulphide reacts on sulphur dioxide.

$$H_2S + 3SO_2 = H_2S_4O_6$$

$H_2S + 3SO_2 = H_2S$ [illegible] $S$

$H_2S_4O_6 + S = H_2S$ [illegible]

The thionic acids probably contain a chain of sulphur atoms, e.g. sodium tetrathionate is probably



$$\mathrm{NaO}-\underset{\underset{\mathrm{O}}{\downarrow}}{\overset{\overset{\mathrm{O}}{\uparrow}}{\mathrm{S}}}-\mathrm{S}-\mathrm{S}-\underset{\underset{\mathrm{O}}{\downarrow}}{\overset{\overset{\mathrm{O}}{\uparrow}}{\mathrm{S}}}-\mathrm{ONa}$$

## HALOGEN COMPOUNDS OF SULPHUR

The affinity of sulphur for the halogens decreases in the order

fluorine > chlorine > bromine > iodine.

The most important halide is commonly known as sulphur monochloride, although its formula is $S_2Cl_2$ (probably Cl—S—S—Cl). It is obtained by passing chlorine over sulphur. It is a good solvent for sulphur and is used during the vulcanization of rubber. It is also used in the preparation of carbon tetrachloride (p. 346) and mustard gas (p. 450).

### Detection and Determination of Sulphur in Organic Compounds

Sulphur may be detected in organic compounds by heating them with metallic sodium. The sulphur is converted to sodium sulphide, which may be detected by the colour formed by the reaction of soluble sulphides with sodium nitroprusside.

Sulphur in organic compounds may be determined by conversion to and weighing as barium sulphate. In the official assay of Ichthammol, the organic substance is destroyed by heating with sodium carbonate and copper nitrate when the sulphur is converted to sulphate. It is precipitated with barium chloride in acid solution. The sulphur present as ammonium sulphate is also assayed. For Stibophen, the organic matter is destroyed by fusion with a mixture of potassium hydroxide and nitrate.

### Selenium and Tellurium

These elements resemble sulphur in their general properties. The ordinary forms of the elements have metallic lustre and slight conductivity. Selenium is peculiar in that light causes its electrical resistance to fall, a property ma[illegible] in some light-sensitive cells. Selenium and tellurium have prog[illegible] less affinity than sulphur for oxygen and hydrogen.

# CHAPTER XI

## NITROGEN

NITROGEN makes up about 78 per cent of the atmosphere, and is present in all living matter. Animals obtain nitrogen from their food. The nitrogen contained in plants is derived from the soil, into which it is introduced in the first place from atmospheric nitrogen, in some cases by the action of bacteria but more generally in the form of nitric acid, small quantities of which are found in the rain of thunderstorms. The necessity to replenish the nitrogen of the soil under modern conditions of agriculture has caused the growth of large-scale processes for the fixation of atmospheric nitrogen.

Nitrogen is obtained commercially from liquid air. In the laboratory it is prepared from compounds containing nitrogen, e.g. by the action of heat on ammonium nitrite, or the action of urea on an acidified solution of sodium nitrite.

$$NH_4NO_2 = 2H_2O + N_2$$

$$2HNO_2 + CO(NH_2)_2 = CO_2 + 2N_2 + 3H_2O$$

Lord Rayleigh found that the nitrogen obtained from chemical sources was slightly lighter than that obtained from the air by removal of the oxygen and the other known constituents. This observation led to the discovery of the inert gases.

## THE ATMOSPHERE

The atmosphere consists of a mixture of various gases, in proportions which vary but slightly. The chief constituents are nitrogen (78 per cent), oxygen (21 per cent), carbon dioxide, water vapour, and the inert gases.

### Liquid Air

Air is liquefied (after drying and removing carbon dioxide) by allowing it to expand from a high pressure (200 atmos.) to a lower pressure (50 atmos.). [A preliminary cooling with liquid ammonia (b.p. — 33°C) is necessary.] The free expansion of the air cools it owing to the work done against the attractions between the molecules of the gas.

Liquid air is a pale blue liquid (which is stored in vacuum jacketed, silver walled "Dewar" flasks). By fractional distillation the nitrogen, oxygen, and the other gases may be separated. Oxygen is slightly less volatile than nitrogen (b.p. oxygen – 183°C, nitrogen – 196°C), so that the gas which escapes first when liquid air is vaporized is pure nitrogen. The liquid which remains becomes richer in oxygen, and by careful fractionation an almost complete separation may be obtained. Commercially, gases containing about 99 per cent oxygen and 99 per cent nitrogen are obtained.

## The Inert Gases

The family of inert gases consists of helium (approximately 0·0005 per cent present in air), neon (0·0015 per cent), argon (0·933 per cent), krypton (0·000005 per cent), and xenon (0·0000006 per cent). A sixth member of the family (radon) is a product of the disintegration of radium (p. 307). Helium was first discovered in the sun by its spectrum. It is one of the products of radioactive disintegration.

The inert gases are separated from liquid air. Helium and neon are not liquefied by the ordinary liquid air apparatus, and escape as gases. Argon, krypton and xenon accumulate in the oxygen fraction when liquid air is fractionally distilled. They are separated by refractionation.

The inert gases are characterized by complete chemical inertness. They form no stable compounds with other elements. Their molecules are monatomic (He, Ne, A, etc.). These elements may be said to possess zero valency. The existence of such elements has played an important part in the understanding of atomic structures and the mechanism of chemical combination (p. 307).

Helium being non-inflammable is used for inflating airships (density of helium twice that of hydrogen, lifting power 92 per cent that of hydrogen). It is extracted from certain natural gases by liquefying the other constituents. Helium was the last gas to be liquefied (b.p. – 268·5°C, f.p. – 272°C at 2·6 atmos.). Neon is used for electric signs, owing to the brilliant red light of its spectrum. Argon and krypton are used as an inert filling for "half watt" lamps, where the presence of an inert gas (instead of a vacuum) enables higher filament temperatures to be used without blackening of the bulb being caused by the volatilization of the metal from the filament.

### Properties of Nitrogen

Nitrogen is a colourless, odourless gas which is less soluble than oxygen in water.

Nitrogen is rather inert chemically, and does not react with ordinary reagents. (This inactivity is probably due to the strength of the linkage between the two nitrogen atoms in the nitrogen molecule, $N \equiv N$. Many compounds containing nitrogen can be obtained, and active forms of nitrogen (e.g. atomic nitrogen) can be prepared.)

Gaseous nitrogen combines on heating with oxygen and hydrogen (both reactions are reversible) and with a few metals (e.g. magnesium). It also reacts with calcium carbide and certain other carbides.

$$N_2 + O_2 \rightleftharpoons 2NO$$

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

$$3Mg + N_2 = Mg_3N_2$$

$$CaC_2 + N_2 = \underset{\text{Calcium cyanamide}}{CaCN_2} + C$$

Nitrogen is usually tervalent (e.g. $NH_3$) or quinquevalent (e.g. $HNO_3$), but some of the oxides of nitrogen exhibit abnormal valencies. The highest oxygenated compound of nitrogen is nitric acid, the most reduced is ammonia. A large number of compounds exist with oxygen or hydrogen contents intermediate between these two substances. They may be converted by oxidation to nitric acid or by reduction to ammonia, and they therefore behave both as reducing and as oxidizing agents.

## COMPOUNDS OF NITROGEN AND HYDROGEN

The chief compounds of nitrogen and hydrogen are ammonia ($NH_3$), hydrazine ($N_2H_4$), and hydrazoic acid ($HN_3$). The first two compounds are basic (forming salts by addition of a molecule of acid), the last compound is acidic. Other hydrides (ammonium hydrazoate $N_4H_4$, and hydrazine hydrazoate $N_5H_5$) can therefore be prepared.

## Ammonia

Ammonia can be prepared in the laboratory by heating an ammonium salt with an alkali, e.g. ammonium chloride with lime.

$$2NH_4Cl + CaO = CaCl_2 + 2NH_3 + H_2O$$

Commercially some ammonia is obtained from the watery ammoniacal liquor obtained during the manufacture of coal gas (p. 223). The ammonia is distilled from this liquor after adding lime, and is absorbed in sulphuric acid. (Ammonium sulphate is used as a fertilizer.) Gas works ammonia may contain volatile organic bases such as pyridine (p. 567), and other tarry matter. These impurities can be detected (as in the official limit test) by neutralizing the ammonia with a weak acid (such as citric acid) which does not combine with the very weak tarry bases. The tar base impurities can then be detected by their strong smells.

Large quantities of ammonia are prepared synthetically by the direct combination of hydrogen with the nitrogen of the air (*Haber* process).

On a commercial scale the hydrogen and nitrogen are prepared by passing steam and air over heated coke.

$$C + H_2O = CO + H_2$$

$$2C + O_2 = 2CO$$

The carbon monoxide is removed by oxidizing it with steam to carbon dioxide which may be absorbed in water.

$$CO + H_2O = CO_2 + H_2$$

After removing the last traces of carbon monoxide by absorption in ammoniacal cuprous chloride solution, the mixed gases are passed over the catalyst. The ammonia formed is separated by condensation to a liquid or by absorption in water. The excess gases are recirculated over the catalyst. The ammonia may be marketed as such or as ammonium salts, or it may be converted into nitric acid (p. 196). Ammonium sulphate is manufactured by reacting on ammonium carbonate with calcium sulphate.

$$(NH_4)_2CO_3 + CaSO_4 = CaCO_3 + (NH_4)_2SO_4$$

The combination of nitrogen and hydrogen is reversible, so that an equilibrium mixture is obtained.

$$\underset{1\ \text{vol}}{N_2} + \underset{3\ \text{vol}}{3H_2} \rightleftharpoons \underset{2\ \text{vol}}{2NH_3}$$

As the reaction to form ammonia takes place with a decrease in volume (1 + 3 = 4 vol. → 2 vol), a larger proportion of ammonia is present in the equilibrium mixture at high pressures (cf. p. 27). In the Haber process, combination is effected at a pressure of 200 atmos. and a temperature of 550°C. Too high a temperature cannot be used as the formation of ammonia is exothermic, and consequently the equilibrium proportion of ammonia decreases as the temperature is raised. At low temperatures the reaction is too slow for economic working, and therefore a compromise temperature must be used. Catalysts (e.g. metallic iron) are added to accelerate the reaction so that as low a temperature as possible can be used to obtain a more complete conversion.

Ammonia is also obtained commercially by hydrolysis of calcium cyanamide.

$$CaCN_2 + 3H_2O = CaCO_3 + 2NH_3$$

Ammonia is the final product of reduction of inorganic nitrogen compounds (cf. assay of Potassium Nitrate, p. 199).

### PROPERTIES OF AMMONIA

Ammonia is a gas with a characteristic smell. It is easily condensed to a liquid (b.p. – 33°C) which is used as a refrigerating agent. Ammonia is very soluble in water. Its solution reacts alkaline to litmus.

### *Formation of Ammonium Salts*

Ammonia is a basic substance, and reacts with acids to form ammonium salts. Salt formation is accompanied by the addition of one molecule of a monobasic acid to ammonia, i.e. the nitrogen passes from the tervalent to the quinquevalent state.

$$NH_3 + HCl = NH_4Cl$$

$$2NH_3 + H_2SO_4 = (NH_4)_2SO_4$$

A group of atoms which passes intact from one compound to another and thus takes the place of a single atom is called a *radical*. The ammonium salts contain the ammonium radical ($NH_4$) which takes the place of a metal. The ammonium salts are similar to those of potassium (with which they are isomorphous) in general chemical properties, but differences arise in reactions causing the complex ammonium radical to be broken down, e.g. by the action of heat or strong alkalis.

On heating, some ammonium salts (e.g. ammonium chloride) dissociate into ammonia and the acid, which recombine on cooling.

$$NH_4Cl \rightleftharpoons NH_3 + HCl$$

The ammonium salts of oxyacids usually decompose irreversibly on heating.

$$NH_4NO_3 = N_2O + 2H_2O$$
$$(NH_4)_2Cr_2O_7 = N_2 + 4H_2O + Cr_2O_3$$

When heated with strong alkalis, ammonium salts are decomposed with evolution of ammonia.

$$NH_4Cl + NaOH = NaCl + NH_3 + H_2O$$

An aqueous solution of ammonia probably contains a certain amount of ammonium hydroxide. It is only weakly basic (although the ammonium salts of strong acids are almost neutral in solution).

$$NH_3 + H_2O \rightleftharpoons NH_4OH \rightleftharpoons NH_4^+ + OH^-$$

*Substitution Reactions of Ammonia*

The hydrogen of ammonia can be substituted—

(1) By sodium or potassium by passing the gas over the heated metal

$$2Na + 2NH_3 = \underset{\text{Sodamide}}{2NaNH_2} + H_2,$$

(2) By chlorine and other halogens. Excess chlorine reacts with ammonia to form the highly explosive nitrogen trichloride.

$$NH_3 + 3Cl_2 = NCl_3 + 3HCl$$

With excess ammonia, nitrogen is obtained.

$$8NH_3 + 3Cl_2 = 6NH_4Cl + N_2$$

Iodine reacts with ammonia to form "nitrogen iodide" (more probably a compound of the formula $NI_3, NH_3$) which is a black, easily exploded substance.

(3) Ammonia may be substituted by organic radicals to form the organic amines (pp. 431–497).

*Oxidation of Ammonia*

Ammonia reacts with oxygen (more rapidly in presence of a platinum catalyst) to form nitric oxide.

$$4NH_3 + 5O_2 = 4NO + 6H_2O$$

This reaction is the basis of the *Ostwald* process for converting ammonia into nitric acid (p. 196).

*Ammonium Carbonate and Bicarbonate*

The combination of ammonia with carbon dioxide in absence of water results in the formation of ammonium carbamate (p. 438).

$$2NH_3 + CO_2 = NH_2.COONH_4$$

In presence of water either ammonium carbonate or bicarbonate can be obtained depending whether excess of ammonia or carbon dioxide is present. Thus when preparing Aromatic Spirit of Ammonia, ammonium carbonate is formed by the action of ammonia on ammonium bicarbonate.

$$NH_3 + CO_2 + H_2O = NH_4HCO_3$$
$$NH_3 + NH_4HCO_3 = (NH_4)_2CO_3$$

Ammonium carbonate can also be obtained by subliming a mixture of ammonium sulphate and calcium carbonate.

$$(NH_4)_2SO_4 + CaCO_3 = (NH_4)_2CO_3 + CaSO_4$$

Ammonium carbonate is less stable than ammonium bicarbonate. It loses ammonia on exposure to air and forms the bicarbonate, and loses water forming the carbamate.

$$(NH_4)_2CO_3 = NH_4HCO_3 + NH_3$$
$$(NH_4)_2CO_3 = NH_2.COONH_4 + H_2O$$

## Determination of Ammonia and Ammonium Salts

Free ammonia can be determined by absorption in standard acid, the excess of which can be found by back titration with standard alkali. Methyl red is a satisfactory indicator for the titration of ammonia with strong acids.

Ammonium salts may be assayed by heating with a known quantity of standard alkali and determining the excess alkali which remains after all the ammonia has been driven off. Alternatively the ammonia formed on heating with the alkali may be determined by absorption in acid and back titration.

Ammonium bicarbonate is determined by a back titration method.

$$2NH_4HCO_3 + H_2SO_4 = (NH_4)_2SO_4 + 2CO_2 + 2H_2O$$

Ammonium salts may also be assayed by addition of formaldehyde, and titrating the liberated acid with standard alkali (p. 376).

Aromatic Spirit of Ammonia is assayed by reacting with barium chloride to convert the ammonium carbonate to barium carbonate and to form an equivalent quantity of ammonium chloride. This is assayed by reaction with formaldehyde using the back titration technique.

$$(NH_4)_2CO_3 + BaCl_2 = BaCO_3 + 2NH_4Cl$$
$$2NH_4Cl = 2NH_3 + 2HCl$$
$$6CH_2O + 4NH_3 = N_4(CH_2)_6 + 6H_2O$$

The free ammonia is determined by the ordinary back titration method, but the result has to be corrected for the acid reacting on the ammonium carbonate

$$NH_3 + HCl = NH_4Cl$$
$$(NH_4)_2CO_3 + 2HCl = 2NH_4Cl + CO_2 + H_2O$$

(Ammonium Chloride is officially assayed on its halide content, p. 121.)

Small quantities of ammonia are detected and determined colorimetrically by adding an alkaline solution of potassium mercuric iodide (Nessler's reagent) with which ammonia forms a brown-coloured solution or precipitate, probably due to the formation of the compound $NH_2Hg_2I_3$.

*Hydrazine.* Hydrazine has the formula $NH_2{-}NH_2$ (di-amine). It can be obtained by gentle oxidation of ammonia (e.g. by sodium hypochlorite in presence of glue).

$$2NH_3 + O = N_2H_4 + H_2O$$

After the oxidation is complete, sulphuric acid is added, and the hydrazine is crystallized in the form of its sulphate.

Hydrazine is a strong base, which combines readily with water to form hydrazine hydrate $N_2H_4, H_2O$. With acids it forms salts such as hydrazine sulphate $N_2H_4, H_2SO_4$, hydrazine monochloride $N_2H_4$, HCl, and hydrazine dichloride $N_2H_4$, 2HCl. It is a powerful reducing agent, [although phenylhydrazine (p. 456) behaves as an oxidizing agent reverting to the ammonia type.

$$C_6H_5NH.NH_2 + H_2 \rightarrow C_6H_5NH_2 + NH_3]$$

*Hydrazoic Acid* ($HN = N \overset{\rightarrow}{=} N$) is a strong acid. Sodium hydrazoate is obtained by reduction of sodium nitrite by hydrazine sulphate, or by passing nitrous oxide over sodamide.

$$N_2H_4 + NaNO_2 = NaN_3 + 2H_2O$$

$$N_2O + NaNH_2 = H_2O + NaN_3$$

The hydrazoates are often called *azides*, and many are explosive. (Lead azide $PbN_6$ is used as a detonating agent instead of mercury fulminate.)

*Hydroxylamine* ($NH_2OH$). Although hydroxylamine contains oxygen it is conveniently discussed here. It is a derivative of ammonia in which one atom of hydrogen has been replaced by a hydroxyl group. Hydroxylamine is obtained by reduction of nitric oxide or nitric acid by tin dissolving in hydrochloric acid.

$$2NO + 3H_2 = 2NH_2OH$$

$$HNO_3 + 3H_2 = NH_2OH + 2H_2O$$

Commercially, hydroxylamine sulphate is obtained by reducing sodium nitrite with sodium sulphite (sulphur dioxide being passed into a solution of sodium nitrite and sodium carbonate).

$$2SO_2 + NaNO_2 + 3H_2O = NaHSO_4 + NH_2OH + H_2SO_4$$

Hydroxylamine, like ammonia, is a base which forms salts by addition of acids. It behaves both as a reducing agent and (in alkaline solutions) as an oxidizing agent, and it is a valuable reagent in organic chemistry (p. 372).

$$2NH_2OH + O_2 = N_2O + 3H_2O$$

$$NH_2OH + H_2 = NH_3 + H_2O$$

## OXIDES AND OXYACIDS OF NITROGEN

Nitrogen forms several oxides (nitrous oxide $N_2O$; nitric oxide NO; nitrogen trioxide $N_2O_3$; nitrogen dioxide $NO_2$; and nitrogen pentoxide $N_2O_5$), and three oxyacids [hyponitrous acid $(HNO)_2$; nitrous acid ($HNO_2$ corresponding to $N_2O_3$); and nitric acid ($HNO_3$ corresponding to $N_2O_5$)].

## / Nitrous Oxide

Nitrous Oxide is prepared by the action of heat on ammonium nitrate.

$$NH_4NO_3 = N_2O + 2H_2O$$

It is compressed into cylinders for use as an anæsthetic, for which purpose the ammonium nitrate used must be free from organic matter and ammonium chloride to prevent the formation of oxides of carbon or chlorine. Before putting into cylinders the gas may be washed with ferrous sulphate solution to remove traces of nitric oxide. Nitrous oxide is a colourless gas with a faint smell. It is appreciably soluble in water, forming a neutral solution. The oxygen is loosely bound to nitrogen in this oxide, and the gas is an active supporter of combustion. When inhaled, it produces anæsthesia.

The official limit of carbon monoxide in Nitrous Oxide is fifty parts per million. The test depends on the reaction with iodine pentoxide at 120°C. Iodine is liberated and is absorbed in potassium iodide solution and determined by titration with thiosulphate (cf. p. 165). Before passing through the iodine pentoxide tube, the gas must be purified to remove other substances (e.g. ethylene) which act on iodine pentoxide.

$$5CO + I_2O_5 = I_2 + 5CO_2$$

Other tests are made for (1) water vapour (by absorption by phosphorus pentoxide); (2) carbon dioxide (by absorption by soda-lime); (3) gases not condensed at liquid air temperature (chiefly nitrogen): (4) arsine and phosphine (by passing the gas through a mercuric chloride paper); (5) halides and hydrogen sulphide, acidity or alkalinity, and oxidizing or reducing substances (by passing the gas through silver nitrate solution, unbuffered methyl red solution at approximately $p$H 5·0, potassium iodide, and potassium permanganate solutions respectively).

## Nitric Oxide

The most stable of the oxides of nitrogen, this is a highly endothermic compound, and is formed by direct union of the two elements at high temperatures.

$$N_2 + O_2 = 2NO - 43{,}200 \text{ cal.}$$

This reaction is utilized for the fixation of atmospheric nitrogen in the *Birkeland-Eyde* process. Air is blown through an electric arc, and the mixed gases are then cooled rapidly. At ordinary temperatures nitric oxide reacts with oxygen to form nitrogen dioxide, which is absorbed in water to form nitric acid (p. 197).

Nitric oxide is also prepared commercially by oxidation of ammonia (p. 185). In the laboratory it is usually prepared by the reduction of nitric acid with metallic copper or ferrous sulphate.

$$3Cu + 8HNO_3 = 3Cu(NO_3)_2 + 4H_2O + 2NO$$

It is also obtained when nitrous acid oxidizes potassium iodide (cf. p. 196).

PROPERTIES OF NITRIC OXIDE

Nitric oxide is a colourless gas. It is slightly soluble in water, but less soluble in saturated brine solution over which it may be collected. It is a fairly stable substance. As nitric oxide is not easily decomposed it does not readily support combustion (but strongly burning phosphorus continues to burn in the gas). Nitric oxide behaves as an unsaturated compound. It reacts rapidly with oxygen to form nitrogen dioxide, and with chlorine to form nitrosyl chloride (NOCl).

$$2NO + O_2 = 2NO_2$$
$$2NO + Cl_2 = 2NOCl$$

The brown ring test for nitrates depends on the formation of a dark brown-coloured addition product of nitric oxide with ferrous salts ($FeSO_4$, NO).

Nitric oxide can be reduced slowly to nitrogen (by heating with carbon or iron), or to hydroxylamine by tin dissolving in hydrochloric acid.

## Nitrogen Dioxide

This is obtained by the action of oxygen on nitric oxide, or by the action of heat on the nitrates of the heavy metals.

$$2Pb(NO_3)_2 = 2PbO + 4NO_2 + O_2$$

It is a red-brown gas which can be condensed to a pale yellow liquid (b.p. 22°C). It freezes (at − 10°C) to a colourless solid.

The change in colour is due to the reversible association and dissociation of the substance.

$$\underset{\text{Brown: Nitrogen dioxide}}{2NO_2} \rightleftharpoons \underset{\text{Colourless: Dinitrogen tetroxide}}{N_2O_4}$$

Nitrogen dioxide dissolves in water, being decomposed into a mixture of nitrous and nitric acids.

$$2NO_2 + H_2O = HNO_2 + HNO_3$$

If the gas is absorbed slowly in presence of air, oxidation takes place and nitric acid is obtained.

$$4NO_2 + 2H_2O + O_2 = 4HNO_3$$

Nitrogen dioxide is absorbed by alkalis forming a mixture of nitrite and nitrate.

$$2NO_2 + 2KOH = KNO_2 + KNO_3 + H_2O$$

Nitrogen dioxide does not part readily with its oxygen (although burning phosphorus continues to burn in the gas). It can be reduced to nitric oxide, which however combines with the oxygen of the air reforming nitrogen dioxide. By alternate reduction and oxidation, this gas acts as a carrier of oxygen in the lead chamber process for the manufacture of sulphuric acid.

*Hyponitrous Acid* $(HNO)_2$ is represented by the formula

$$HO-N=N-OH$$

(cf. oximes, p. 373). Its salts are obtained by the reduction of nitrites by sodium amalgam.

$$2KNO_2 + 2H_2 = 2H_2O + K_2O_2N_2$$

The acid is unstable, and explosive. It decomposes slowly into nitrous oxide and water. It is a strong reducing agent.

$$H_2O_2N_2 = H_2O + N_2O$$

$$H_2O_2N_2 + 2O_2 = 2HNO_3$$

## Nitrous Acid

When sodium or potassium nitrate is heated, oxygen is evolved and the nitrite is obtained. The decomposition is facilitated by the presence of metallic lead which assists in the removal of the oxygen.

$$2NaNO_3 = 2NaNO_2 + O_2$$
$$NaNO_3 + Pb = NaNO_2 + PbO$$

The nitrite is separated from the lead oxide by dissolving in water. The solution is neutralized (to remove traces of sodium hydroxide formed during the fusion) and evaporated to crystallization point. Sodium nitrite occurs as colourless or pale yellow deliquescent crystals.

Nitrous acid is a weak acid and it is easily displaced from its salts by other acids. It is unstable and readily breaks down into nitric oxide and nitrogen dioxide.

$$NaNO_2 + HCl = NaCl + HNO_2$$
$$2HNO_2 = NO + NO_2 + H_2O$$

Pure nitrous acid has not been isolated, although its anhydride ($N_2O_3$) has been obtained as blue crystals (m.p. – 103°C) by reacting on nitric oxide with nitrogen dioxide.

$$NO + NO_2 = N_2O_3$$

Nitrous anhydride decomposes rapidly at ordinary temperatures, but the blue colour of the solution obtained by adding dilute acid to a cold solution of a nitrite is probably due to the presence of this compound.

Nitrous acid is a powerful oxidizing agent. It liberates iodine from an acidified solution of an iodide, and is converted into nitric oxide.

$$2KNO_2 + 2KI + 4HCl = 2NO + I_2 + 4KCl + 2H_2O$$

Further reduction of nitrites (e g. with a zinc-copper couple) yields ammonia.

$$HNO_2 + 3H_2 = NH_3 + 2H_2O$$

Nitrous acid also behaves as a reducing agent for it may be oxidized to nitric acid, e.g. by potassium permanganate.

$$HNO_2 + O = HNO_3$$

The formula of nitrous acid is represented by $HO - N = O$. The corresponding acid chloride (nitrosyl chloride NOCl) is present in *aqua regia*. It can be prepared by reacting on nitric oxide with chlorine or by the reaction of phosphorus pentachloride with a nitrite.

### DETERMINATION OF NITRITES

Nitrites may be determined by reduction to nitric oxide by hydriodic acid (as in the official method of assay of Spirit of Nitrous Ether and of Amyl Nitrite, p. 397), or by oxidation to nitric acid by potassium permanganate.

$$\begin{aligned} & 2C_2H_5NO_2 + 2KI + 2HCl \\ & \qquad = 2NO + I_2 + 2C_2H_5OH + 2KCl \end{aligned}$$

$$\begin{aligned} & 5NaNO_2 + 2KMnO_4 + 3H_2SO_4 \\ & \qquad = 5NaNO_3 + K_2SO_4 + 2MnSO_4 + 3H_2O \end{aligned}$$

For the latter method (as in the official method for the assay of Sodium Nitrite) it is not possible to acidify the nitrite solution and add the permanganate solution from the burette owing to the ease of decomposition of nitrous acid. Instead the acidified permanganate solution is placed in a titration flask, and the nitrite is added from the burette until the permanganate colour just disappears. The titration is carried out at 40°C to hasten the reaction.

## ✓ Nitric Acid

This is obtained from sodium nitrate, which is found as a deposit in Chile (Chile saltpetre or caliche). The crude nitrate contains sodium chloride and various oxy-halogen salts such as sodium iodate. It is purified by recrystallization from water.

When heated with concentrated sulphuric acid, sodium nitrate yields nitric acid, which distils and is condensed in earthenware pots.

$$NaNO_3 + H_2SO_4 = HNO_3 + NaHSO_4$$

The residue of sodium acid sulphate (nitre cake) cannot be used for conversion of further quantities of sodium nitrate into nitric acid as the high temperature necessary to bring about the change would decompose the nitric acid formed.

Nitric acid is also obtained commercially by oxidation of ammonia to nitric oxide by air in presence of a catalyst (platinum). The nitric oxide is absorbed in water in presence of air and yields nitric acid. The nitric oxide prepared by the Birkeland-Eyde process (p. 193) is also converted into nitric acid in the same way. The dilute acid which is formed is concentrated by adding sulphuric acid and distilling.

Nitric acid, when pure, is a colourless fuming liquid, which decomposes slightly on heating so that normal samples are pale yellow in colour owing to the presence of nitrogen dioxide. The commercial nitric acid is the constant boiling mixture (b.p. 121°C, 68% nitric acid). Nitric acid in presence of water behaves as a strong acid, which dissolves metals, and reacts with bases to form nitrates. With the exception of those of certain organic bases, nitrates are soluble in water.

Nitric acid is also a powerful oxidizing agent. It readily oxidizes iodides, ferrous salts, sulphur, phosphorus, and many organic substances (e.g. sugar is oxidized to oxalic acid).

$$6KI + 8HNO_3 = 3I_2 + 6KNO_3 + 4H_2O + 2NO$$

$$6FeCl_2 + 6HCl + 2HNO_3 = 6FeCl_3 + 4H_2O + 2NO$$

$$S + 2HNO_3 = H_2SO_4 + 2NO$$

$$3P + 5HNO_3 + 2H_2O = 3H_3PO_4 + 5NO$$

$$C_{12}H_{22}O_{11} + 12HNO_3 = 6H_2C_2O_4 + 11H_2O + 12NO$$

Nitric acid, owing to its oxidizing action, seldom yields hydrogen when it reacts on metals. Nitric oxide is obtained by dissolving copper, mercury or lead in nitric acid; other metals such as zinc cause the nitric acid to be reduced further, and nitrous oxide, nitrogen or ammonia may be obtained depending on the conditions.

$$3Cu + 8HNO_3 = 3Cu(NO_3)_2 + 2NO + 4H_2O$$

$$4Zn + 10HNO_3 = 4Zn(NO_3)_2 + NH_4NO_3 + 3H_2O$$

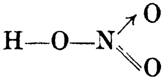
Nitric acid reacts with hydrochloric acid forming chlorine and nitrosyl chloride. Owing to the presence of the free chlorine the mixture of the two acids (*aqua regia*) forms a solvent for metals like gold which are insoluble in the single acids.

$$3HCl + HNO_3 = Cl_2 + NOCl + 2H_2O$$

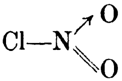
Nitric acid is important in organic chemistry for its reactions to form nitrate esters (e.g. nitroglycerin, nitrocellulose, p. 396) and the nitro derivatives (e.g. nitrobenzene, p. 497). Many of these compounds are powerful explosives.

The anhydride of nitric acid ($N_2O_5$) is prepared by the reaction of phosphorus pentoxide on nitric acid. It is a crystalline solid, and a powerful oxidizing agent.

*Constitution of Nitric Acid.* Nitric acid has the formula



the corresponding acid chloride being nitroxyl chloride ($NO_2Cl$).



THE NITRATES

The nitrates are conveniently prepared by reaction of nitric acid on the metal, metallic oxide, or hydroxide. *Sodium Nitrate* and *Potassium Nitrate* (saltpetre) occur naturally. They have probably been formed by the decay of nitrogenous organic matter in contact with alkaline substances. The ammonia formed during the first stages of decomposition becomes oxidized to nitric acid by bacterial action.

Potassium nitrate is less hygroscopic than sodium nitrate, and is therefore more convenient for many purposes. Considerable quantities of sodium nitrate are converted into potassium nitrate by dissolving in hot water and mixing with a hot solution of potassium chloride. After removing the less soluble sodium chloride by filtration, the hot solutions are cooled, when potassium nitrate crystallizes out. The conversion depends upon the relative solubilities of the four salts, sodium and potassium chlorides and nitrates (Fig. 20).

Most nitrates are decomposed on heating. Potassium and sodium nitrates on heating evolve oxygen, and are converted to nitrites.

$$2KNO_3 = 2KNO_2 + O_2$$

The nitrates of the heavy metals evolve nitrogen dioxide and oxygen, and form the metal oxide. Nitric acid decomposes in a similar manner.

$$2Pb(NO_3)_2 = 2PbO + 4NO_2 + O_2$$

Ammonium nitrate on heating is decomposed to nitrous oxide and water.

$$NH_4NO_3 = N_2O + 2H_2O$$

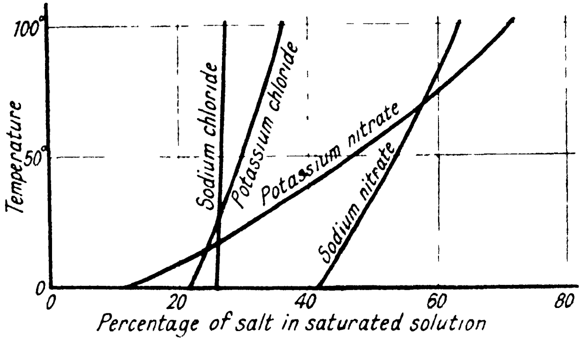


FIG. 20. SOLUBILITY CURVES OF SALTS IN WATER

DETERMINATION OF NITRIC ACID AND NITRATES

Nitric acid is assayed by direct titration with standard alkali. Potassium Nitrate is assayed by dissolving in dilute nitrogen-free sulphuric acid and adding reduced iron, whereby the hydrogen evolved by the solution of the iron reduces the nitrate to ammonia which forms ammonium sulphate.

$$8H_2 + 2KNO_3 + 2H_2SO_4 = (NH_4)_2SO_4 + K_2SO_4 + 6H_2O$$

Excess alkali is added, and the ammonia formed is distilled into a known volume (excess) of standard acid, the excess acid being determined by back titration. A blank experiment is necessary to allow for traces of combined nitrogen in the reagents. (For this method it is essential that the Potassium Nitrate should be free from ammonium salts; this is ensured by an official limit test.)

$$KNO_3 \equiv NH_3$$

Small quantities of nitrates (e.g. as impurities in other substances, e.g. Bismuth Carbonate) may be determined by taking advantage of the oxidizing action of nitric acid on indigo carmine. Indigo carmine is a deep blue substance which is oxidized to an almost colourless product. Alternatively, nitrates may be detected by colour reactions with organic compounds such as phenoldisulphonic acid or diphenylamine.

## Detection and Determination of Nitrogen in Organic Compounds

Nitrogen may be detected in organic compounds by heating them with metallic sodium. Sodium cyanide is formed, and may be detected by conversion to Prussian blue (cf. p. 297).

The nitrogen content of organic compounds may be determined by two methods.

(1) *Dumas' Method.* The compound is mixed with copper oxide and burnt in a stream of carbon dioxide. The escaping gases are passed over heated copper (to reduce any nitrogen oxides that may have been formed), and collected over potassium hydroxide solution (to absorb the carbon dioxide). The volume of nitrogen collected (which represents the whole of the nitrogen contained in the organic compound) is measured.

(2) *Kjeldahl's Method.* This method is used for the official assay of the nitrogen content of Extract of Malt, Diphenan, Mersalyl, Neostigmine, Nikethamide, Riboflavin and Tryparsamide. The organic substance is heated for several hours with concentrated sulphuric acid containing potassium bisulphate, whereby the organic matter is completely destroyed and the nitrogen is converted to ammonium sulphate. (The addition of selenium accelerates the decomposition of the organic substance.) After cooling, and diluting, the ammonium sulphate formed is determined by adding alkali and distilling into excess standard acid, the excess being determined by back titration. A blank determination is necessary to allow for combined nitrogen present in the reagents.

Organic substances which are convertible easily into ammonia by alkali (e.g. Nicotinamide, Saccharin) are assayed directly by this method without the preliminary destruction of the organic matter with sulphuric acid.

# CHAPTER XII

# PHOSPHORUS, ARSENIC, ANTIMONY, AND BISMUTH

THE five elements, nitrogen, phosphorus, arsenic, antimony and bismuth form a family and show definite resemblances to one another. The properties of the elements and their compounds show gradual changes from gaseous, typically non-metallic nitrogen to metallic bismuth. Nitrogen and phosphorus are both definitely non-metallic; metallic properties first appear with arsenic and increase to bismuth.

All five elements form compounds with valencies three and five. The quinquevalent oxides are acidic, the tervalent oxides of nitrogen and phosphorus are acidic, those of arsenic and antimony are amphoteric, while bismuthous oxide is basic. The compounds with hydrogen (which rapidly decrease in stability and basicity from nitrogen to bismuth) again indicate the general relationship between these elements.

Because of this family relationship, arsenic, antimony and bismuth are discussed here instead of with the metals.

## PHOSPHORUS

A complex calcium fluorophosphate (apatite) is found in igneous rocks. The phosphorus present in iron ores is isolated as "basic slag" and sold as a source of phosphorus for fertilizers. Phosphorus is an essential constituent of animal and vegetable tissues, and animal remains left buried in rocks sometimes become transformed into "phosphatic nodules" (usually calcium phosphate) which are worked for their phosphorus content. Bone ash, the residue obtained when bones are calcined, consists mainly of calcium phosphate and is also an important source of phosphorus.

### MANUFACTURE OF PHOSPHORUS

Phosphorus is obtained by reduction of the phosphoric acid obtained from calcium phosphate by heating it with acid, On a large scale, calcium phosphate is heated with silica and carbon in an electric furnace. Crude white phosphorus distils.

$$2Ca_3(PO_4)_2 + 6SiO_2 + 10C = 6CaSiO_3 + 10CO + P_4$$

### Properties of Phosphorus

White phosphorus is a white or pale yellow, translucent, waxy solid, soluble in carbon disulphide. It is very reactive. It glows in air (due to its slow oxidation), and readily catches fire. When heated with a catalyst out of contact of air, it changes into a more stable and less reactive form (red phosphorus) which is non-poisonous and insoluble in carbon disulphide. Red phosphorus is more stable than the white form at all temperatures (contrast the allotropy of sulphur). It can only be transformed into white phosphorus by vaporizing. Phosphorus vapour condenses into white phosphorus.

Phosphorus combines readily with most elements. With metals it forms phosphides which contain tervalent phosphorus. Some phosphides react with water to form phosphorus hydride (phosphine) (cf. nitrides).

$$Ca_3P_2 + 6H_2O = 3Ca(OH)_2 + 2PH_3$$

With oxygen, chlorine and sulphur, compounds are formed containing tervalent and quinquevalent phosphorus.

### Hydrides of Phosphorus

Phosphine ($PH_3$) is prepared by the reaction of white phosphorus on an alkali.

$$P_4 + 3KOH + 3H_2O = PH_3 + \underset{\substack{\text{Potassium}\\ \text{hypophosphite}}}{3KH_2PO_2}$$

The reaction must be carried out in absence of air, as the product is spontaneously inflammable (pure phosphine is not spontaneously inflammable).

Phosphine has very faint basic properties; it is a very much weaker base than ammonia. It forms compounds corresponding to the ammonium salts, e.g. phosphonium iodide ($PH_4I$), but these are rapidly hydrolyzed by water.

$$PH_3 + HI = PH_4I$$

Other compounds of phosphorus and hydrogen are known. A liquid hydride ($P_2H_4$, cf. hydrazine $N_2H_4$) is present in the phosphine prepared by the above reaction, and is the cause of its spontaneous inflammability.

## OXIDES AND OXYACIDS OF PHOSPHORUS

The important oxides of phosphorus are phosphorous oxide ($P_4O_6$) and phosphoric oxide ($P_4O_{10}$). These oxides are acidic oxides and with water they form phosphorous and phosphoric acids ($H_3PO_3$ and $H_3PO_4$) respectively. Phosphorus also forms other oxy-acids, e.g. hypophosphorous acid ($H_3PO_2$), hypophosphoric acid ($H_4P_2O_6$), and the perphosphoric acids ($H_3PO_5$ and $H_4P_2O_8$).

### Hypophosphorous Acid

The hypophosphites are obtained when white phosphorus reacts with alkalis forming phosphine. In order to obtain the acid, phosphorus may be boiled with barium or calcium hydroxide, and the barium or calcium hypophosphite formed may be decomposed with dilute sulphuric acid or oxalic acid.

$$Ca(H_2PO_2)_2 + H_2SO_4 = CaSO_4 + 2H_3PO_2$$

$$Ca(H_2PO_2)_2 + H_2C_2O_4 = CaC_2O_4 + 2H_3PO_2$$

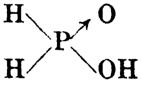
After filtration, the acid is concentrated to a syrupy liquid by evaporation under reduced pressure (since on heating to higher temperatures the acid decomposes into phosphine and phosphoric acid).

$$2H_3PO_2 = PH_3 + H_3PO_4$$

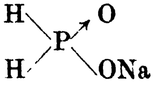
Although the acid contains three atoms of hydrogen, it is a monobasic acid, only one atom being replaceable by metals. The equation for the neutralization of the acid by sodium hydroxide is therefore

$$NaOH + H_3PO_2 = NaH_2PO_2 + H_2O$$

The formulae of hypophosphorous acid and the hypophosphites are probably



and



Hypophosphorous acid and its salts are very strong reducing agents. They reduce mercuric salts to mercurous salts and to mercury, and they reduce copper sulphate solution with the formation of a brownish precipitate of copper hydride ($CuH_2$). The use of hypophosphorous acid in certain official preparations depends on its reducing properties.

### Phosphorous Oxide ($P_4O_6$)

A crystalline substance obtained by burning phosphorus in a limited supply of air, this substance readily reacts with water forming phosphorous acid.

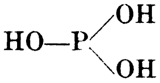
$$P_4O_6 + 6H_2O = 4H_3PO_3$$

Phosphorous acid is also obtained by the action of water on the corresponding acid chloride (phosphorus trichloride).

Phosphorous acid like hypophosphorous acid decomposes on heating.

$$4H_3PO_3 = PH_3 + 3H_3PO_4$$

Its salts are reducing agents and are readily oxidized to phosphates. Phosphorous acid is a tribasic acid of the formula



$$HO{-}P(OH)_2$$

### Phosphoric Oxide and Phosphoric Acid

Phosphoric oxide ($P_4O_{10}$) is obtained when phosphorus is burnt in an unlimited supply of air. Molecular weight determinations reveal its formula to be $P_4O_{10}$.

$$P_4 + 5O_2 = P_4O_{10}$$

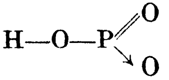
Phosphoric oxide combines with water with great avidity, and it is one of the most powerful drying agents known. With cold water it forms metaphosphoric acid, but on heating in presence of water orthophosphoric acid is formed. A third acid, pyrophosphoric acid, is obtained when orthophosphoric acid is strongly heated.

$$P_4O_{10} + 2H_2O = \underset{\substack{\text{Metaphosphoric}\\ \text{acid}}}{4HPO_3}$$

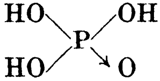
$$P_4O_{10} + 6H_2O = \underset{\substack{\text{Orthophosphoric}\\ \text{acid}}}{4H_3PO_4}$$

$$2H_3PO_4 = \underset{\text{Pyrophosphoric acid}}{H_4P_2O_7} + H_2O$$

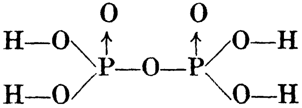
The relationship of these acids is shown by their formulae—



Metaphosphoric acid



Orthophosphoric acid



Pyrophosphoric acid

The most important acid is orthophosphoric acid (usually known as phosphoric acid).

Phosphoric acid is obtained from calcium phosphate by treatment with dilute sulphuric acid. The calcium sulphate is removed by filtration, and after removal of arsenic as arsenious sulphide, the phosphoric acid is concentrated to a syrupy liquid.

$$Ca_3(PO_4)_2 + 3H_2SO_4 = 3CaSO_4 + 2H_3PO_4$$

Phosphoric acid is obtained from phosphorus by oxidizing the vapour directly to phosphoric oxide. It can also be prepared by oxidizing red phosphorus with nitric acid.

$$3P + 5HNO_3 + 2H_2O = 3H_3PO_4 + 5NO$$

Phosphoric acid is a tribasic acid, i.e. it contains three hydrogen atoms replaceable by a metal. It forms three classes of salts (e.g. $NaH_2PO_4$, $Na_2HPO_4$ and $Na_3PO_4$). Monosodium dihydrogen phosphate (sodium acid phosphate) dissolves in water to form an acid solution, disodium monohydrogen phosphate (ordinary sodium phosphate) forms an almost neutral solution, while trisodium phosphate forms a strongly alkaline solution when dissolved in water.

### ASSAY OF PHOSPHORIC ACID AND THE PHOSPHATES

Phosphoric acid, could be determined by titration with standard alkali in accordance with any of the three following equations provided the end-point is chosen to correspond with the formation of the particular salt.

$$H_3PO_4 + NaOH = NaH_2PO_4 + H_2O$$

$$H_3PO_4 + 2NaOH = Na_2HPO_4 + 2H_2O$$

$$H_3PO_4 + 3NaOH = Na_3PO_4 + 3H_2O$$

Fig. 21 represents a titration curve of phosphoric acid with sodium hydroxide, and indicates the formation of the three salts.

Sodium acid phosphate and sodium phosphate are formed with solutions of these concentrations at *p*H values of 4·5 and 9·2 respectively. Therefore if phosphoric acid is titrated using an indicator which changes colour at *p*H 4·5, the reaction is represented by—

$$H_3PO_4 + NaOH = NaH_2PO_4 + H_2O$$

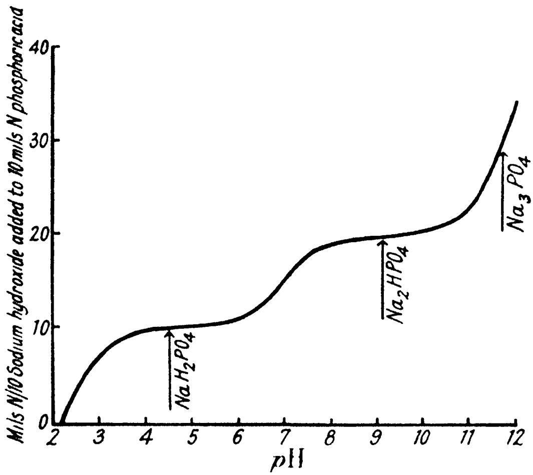


FIG. 21. TITRATION OF PHOSPHORIC ACID

and if the titration is carried out with an indicator changing at *p*H 9·2 the reaction is represented by the equation—

$$H_3PO_4 + 2NaOH = Na_2HPO_4 + 2H_2O$$

Officially, Phosphoric Acid and Sodium Acid Phosphate are both assayed by titration with standard alkali until converted into disodium monohydrogen phosphate. Phenolphthalein is used as the indicator, and sodium chloride is added possibly to obtain a more accurate end-point.

$$NaH_2PO_4 + NaOH = Na_2HPO_4 + H_2O$$

Sodium Phosphate is assayed by titration with acid until converted into sodium acid phosphate.

$$2Na_2HPO_4 + H_2SO_4 = Na_2SO_4 + 2NaH_2PO_4$$

The end-point is reached when the solution gives a colour with bromocresol green corresponding to *p*H 4·5. If a standard buffer solution (*p*H 4·5) is prepared, and bromocresol green added, the end-point of the titration corresponds to an exact match between the colour of this standard solution and that of the solution being titrated.

### Salts of Phosphoric Acid

The alkali metal phosphates are soluble in water, but most other metal phosphates are insoluble.

From the naturally occurring calcium phosphate (which is not very soluble) the soluble calcium acid phosphate is obtained by treatment with dilute sulphuric acid.

$$Ca_3(PO_4)_2 + 2H_2SO_4 = 2CaSO_4 + Ca(H_2PO_4)_2$$

The soluble acid phosphate is a more suitable product for use as a fertilizer than the insoluble normal phosphate. It is sold under the name of superphosphate of lime.

By reacting with sodium carbonate on a solution of calcium acid phosphate, sodium phosphate is obtained.

$$Ca(H_2PO_4)_2 + 2Na_2CO_3 = 2Na_2HPO_4 + CaCO_3 + CO_2 + H_2O$$

After filtration the sodium phosphate is crystallized. It crystallizes with twelve molecules of water of crystallization ($Na_2HPO_4, 12H_2O$). It is efflorescent in dry air.

Sodium acid phosphate is prepared by adding the calculated quantity of phosphoric acid to a solution of sodium phosphate. It crystallizes with two molecules of water of crystallization ($NaH_2PO_4, 2H_2O$). On heating to 300–400°C it is converted to sodium hexametaphosphate, which is used for water softening, since it forms a soluble complex anion containing calcium or magnesium.

$$Na_2HPO_4 + H_3PO_4 = 2NaH_2PO_4$$

$$6NaH_2PO_4 = Na_6P_6O_{18} + 6H_2O$$

For medicinal purposes, Calcium Phosphate is prepared by precipitation, by adding calcium chloride to an ammoniacal solution of sodium phosphate. The precipitate formed consists of normal calcium phosphate; but as the precipitate is dried, hydrolysis takes place and the product contains a variable proportion of calcium acid phosphate and basic calcium phosphate.

$$3Ca_3(PO_4)_2 + 4H_2O = Ca(H_2PO_4)_2 + 2[Ca_3(PO_4)_2, Ca(OH)_2]$$

The substance is assayed on its calcium content (p. 257). Calcium phosphate is insoluble in alkaline solutions; when testing for lead it is retained in solution by the presence of ammonium citrate.

*Phosphates may be detected* by the formation of a yellow precipitate of ammonium phosphomolybdate $[(NH_4)_3PO_4, 12MoO_3]$ when warmed with ammonium molybdate solution in presence of nitric acid.

## Phosphorus Chlorides

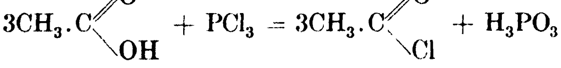
*Phosphorus Trichloride* is prepared by direct union of chlorine with excess of phosphorus. It is a liquid which is very readily hydrolyzed to phosphorous acid.

$$PCl_3 + 3HOH = 3HCl + P(OH)_3$$

Phosphorus trichloride reacts similarly with other substances which contain a hydroxyl group, and it is a very valuable reagent for detecting the presence of these groups in inorganic and organic compounds.

$$PCl_3 + 3ROH = 3RCl + H_3PO_3$$

$$\underset{\text{Sulphuric acid}}{3SO_2(OH)_2} + 2PCl_3 = 3SO_2Cl_2 + 2H_3PO_3$$



$$3CH_3.C\begin{matrix}\nearrow O\\ \searrow OH\end{matrix} + PCl_3 = 3CH_3.C\begin{matrix}\nearrow O\\ \searrow Cl\end{matrix} + H_3PO_3$$

Acetic acid

$$\underset{\text{Ethyl alcohol}}{3C_2H_5OH} + PCl_3 = 3C_2H_5Cl + H_3PO_3$$

*Phosphorus Pentachloride* is prepared by union of chlorine with phosphorus trichloride. It exists only in the solid state and, when vaporized, it is dissociated into the trichloride and chlorine.

$$PCl_3 + Cl_2 \rightleftharpoons PCl_5$$

Phosphorus pentachloride is hydrolyzed into phosphoric acid, and reacts with substances containing hydroxyl groups in a similar way to the trichloride.

When phosphorus pentachloride is hydrolyzed by a limited supply of water, phosphorus oxychloride is obtained. This compound is also formed when phosphorus pentachloride reacts with certain organic compounds (e.g. aldehydes and ketones).

$$PCl_5 + H_2O = 2HCl + POCl_3$$

$$(CH_3)_2CO + PCl_5 = (CH_3)_2CCl_2 + POCl_3$$

### Determination of Phosphorus

Compounds of phosphorus (inorganic or organic) may be determined by oxidation to phosphoric acid and precipitation with a magnesium salt (p. 253).

## ARSENIC

Arsenic occurs as the sulphides termed realgar ($As_2S_2$) and orpiment ($As_2S_3$) but the chief source is arsenical pyrites. Iron pyrites normally contains a certain proportion of arsenic taking the place of sulphur (e.g. mispeckel is FeAsS). By heating arsenical pyrites, arsenic metal is obtained as a crystalline sublimate.

$$FeAsS = FeS + As$$

(When pyrites is burnt, the arsenic is oxidized and is carried away with the sulphur dioxide.)

Traces of arsenic are widely scattered. Coal contains a small quantity of arsenic, which as the coal is burnt escapes as dust into the air. Most substances which have been exposed to atmospheric contamination during manufacture or storage contain traces of arsenic, and a delicate test is necessary to control the quantity of this dangerous impurity.

The ordinary form of arsenic possesses metallic lustre and is a conductor of electricity. A non-metallic, less stable allotropic form can also be obtained. Both forms have molecular weights agreeing with the formula $As_4$.

Arsenic is stable in air at ordinary temperatures, but on heating it burns, forming the oxide ($As_4O_6$). Arsenic combines readily with chlorine. The formation of arsine ($AsH_3$) when hydrogen is being generated in a solution containing arsenic enables small quantities of arsenic to be detected and determined (cf. arsenic limit test, p. 130.)

Arsine is formed readily from metallic arsenic or arsenious compounds, but arsenic compounds should first be reduced to the arsenious state.

**Arsine** is a colourless poisonous gas, which is decomposed by heating.

$$2AsH_3 = 2As + 3H_2$$

In Marsh's test for arsenic, the arsine is decomposed by passing through a heated tube, when a deposit of metallic arsenic is obtained. In the official test, the arsine is detected by its reaction on mercuric chloride to produce a yellow-brown coloured substance.

## THE OXIDES OF ARSENIC

Arsenic forms tervalent and quinquevalent oxides.

### ARSENIC TRIOXIDE

Arsenious oxide, as this is also called, is obtained as a sublimate when arsenical pyrites is roasted in air. It is purified by resublimation.

$$4FeAsS + 10\ O_2 = 2Fe_2O_3 + As_4O_6 + 4SO_2$$

Arsenious oxide crystallizes in two forms, and a third glassy form can also be obtained. It sublimes without melting at about 200°C, forming the vapour whose density corresponds with the formula $As_4O_6$. (The half formula $As_2O_3$ is often used for simplicity of representation.)

Arsenious oxide is sparingly soluble in water, but as it dissolves very slowly, the official Arsenical Solution is prepared by dissolving in alkali and then neutralizing with acid.

Arsenious oxide is an amphoteric oxide. It dissolves in moderately concentrated acids forming arsenious salts, which are hydrolyzed in dilute solution.

$$As_4O_6 + 12HCl \rightleftharpoons 4AsCl_3 + 6H_2O$$

Arsenious salts are oxidized to the arsenic state, e.g. by treatment with bromine water, or iodine (as in the assay of arsenious compounds).

Arsenious oxide dissolves more readily in alkalis than in acids. The arsenites which are formed are salts either of arsenious acid ($H_3AsO_3$), or of metarsenious acid ($HAsO_2$).

$$As_4O_6 + 12NaOH = 4Na_3AsO_3 + 6H_2O$$

$$As_4O_6 + 4NaOH = 4NaAsO_2 + 2H_2O$$

More complex arsenites may also be obtained. The thioarsenites in which sulphur replaces the oxygen of the arsenites (e.g. $KAsS_2$) are obtained by the action of alkaline sulphides (e.g. ammonium sulphide) on arsenious sulphide.

### ARSENIC OXIDE

Arsenic oxide ($As_4O_{10}$) is obtained when arsenious oxide is oxidized by nitric acid. It reacts with water to form arsenic acid. The arsenates are isomorphous with the phosphates (e.g. sodium arsenate $Na_2HAsO_4$). Sodium arsenate is prepared by oxidation of sodium arsenite.

The thio-arsenates (in which the oxygen of the arsenates has been replaced by sulphur, e.g. $Na_3AsS_4$) are obtained when arsenic sulphide dissolves in a solution of ammonium sulphide.

### Arsenious Chloride

This is prepared from the metal by direct combination with chlorine, or by dissolving arsenious oxide in concentrated hydrochloric acid.

$$2As + 3Cl_2 = 2AsCl_3$$

$$As_4O_6 + 12HCl = 4AsCl_3 + 6H_2O$$

It is a volatile substance, which can be distilled unchanged from solutions containing hydrochloric acid. The volatility enables arsenic to be separated from those metals whose chlorides are not volatile (p. 134).

### Arsenious Iodide

Prepared by direct union of arsenic and iodine, arsenious iodide is soluble in water, forming a colourless solution, which is acid owing to hydrolysis.

$$AsI_3 + 3H_2O = H_3AsO_3 + 3HI$$

## Determination of Arsenic

Arsenious compounds are officially assayed by quantitative oxidation to the quinquevalent state by titration with iodine.

$$As_4O_6 + 4I_2 + 10H_2O = 4H_3AsO_4 + 8HI$$

This oxidation is reversible. The reaction proceeds quantitatively from left to right when the solution is kept approximately neutral. For this reason, excess sodium bicarbonate is added in order to neutralize the acids formed during the titration. (Sodium hydroxide could not be used as it reacts with iodine.)

The reverse reaction which proceeds quantitatively in strongly acid solution is the basis of the volumetric method of assay of arsenates. Iodine is liberated, and may be determined by titration with standard sodium thiosulphate solution.

$$2H_3AsO_4 + 10HI \underset{\text{Neutral}}{\overset{\text{Acid}}{\rightleftharpoons}} 2AsI_3 + 2I_2 + 8H_2O$$

## ANTIMONY

The chief ore of antimony is antimony sulphide, from which the metal is obtained by reduction by heating with metallic iron.

$$Sb_2S_3 + 3Fe = 3FeS + 2Sb$$

Crude antimony contains arsenic, and this is removed by heating with a mixture of sodium sulphate and the ferrous sulphide slag obtained in the preparation of the crude metal. [The separation of the arsenic depends on the preferential conversion into a thio-salt ($NaAsS_2$).]

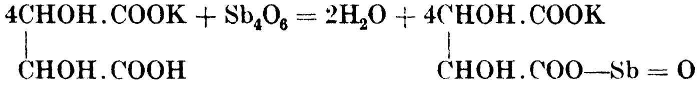
Antimony is a lustrous metal. It expands on solidifying, so that antimony alloys are particularly suitable as type metals, as their expansion produces clear impressions of the moulds. A non-metallic allotropic form of antimony can also be obtained.

Antimony is a less reactive metal than arsenic. It combines readily with chlorine, and on heating in air it forms the oxide. The hydride (stibine $SbH_3$) is obtained when hydrogen is generated in presence of an antimony compound, but it is more easily decomposed than arsine. When stibine is passed through a heated tube, antimony is deposited. It may be distinguished from the arsenic deposited from arsine by the solubility of arsenic in sodium hypochlorite solution. Further, when the arsenic is dissolved in dilute nitric acid, the solution gives a precipitate of silver arsenite with silver nitrate; antimony gives no corresponding precipitate.

## Compounds of Antimony

Antimony forms tervalent and quinquevalent oxides ($Sb_4O_6$ and $Sb_2O_5$). Antimonious oxide is amphoteric. It dissolves in acids to form antimony salts (which are more stable than the arsenious salts), and in alkalis to form antimonites. Antimonic oxide is an acid oxide corresponding to the antimonates (e.g. $NH_4SbO_3$). Antimony also forms an oxide $SbO_2$, which is the most stable oxide at moderate temperatures. It has no marked acid or alkaline reaction on litmus, but salts derived from it (e.g. $SbCl_4$ and $K_2Sb_2O_5$) can be prepared. The corresponding sulphide ($Sb_2S_4$) is precipitated by the action of hydrogen sulphide on a quinquevalent antimony compound.

*Antimonious Oxide* is obtained by heating the metal or sulphide in air. It dissolves in hydrochloric acid to form antimony trichloride, and in solutions of sodium or potassium hydrogen tartrates to form the antimonyl tartrates.



$$4\begin{array}{l}\text{CHOH.COOK}\\ |\\ \text{CHOH.COOH}\end{array} + Sb_4O_6 = 2H_2O + 4\begin{array}{l}\text{CHOH.COOK}\\ |\\ \text{CHOH.COO—Sb} = \text{O}\end{array}$$

*Potassium Antimonyl Tartrate* differs from *Sodium Antimonyl Tartrate* in that it crystallizes with water of crystallization ($2C_4H_4O_7KSb, H_2O$). The simplest method of expressing the formula of the alkali metal antimonyl tartrates is indicated in the above equation. These simple formulae are not completely satisfactory, and other more complex structures have been assigned to these compounds. There is, as yet, no general agreement as to their correct formulae.

*Antimony Trichloride* is prepared by reacting on antimony with chlorine. It is easily hydrolyzed when dissolved in water, and a basic chloride is precipitated.

$$SbCl_3 + H_2O = SbOCl + 2HCl$$

Antimony chloride is volatile and can be distilled in presence of concentrated hydrochloric acid. It is not so volatile as arsenious chloride (b.p. 223°C, arsenious chloride 130°C) so that it can be separated from arsenious chloride by redistillation (cf. arsenic limit test, p. 134).

*Antimonites* are formed when antimonious oxide is dissolved in strong alkalis (so that antimony compounds may be retained in solution during the lead limit test by using sodium hydroxide solution instead of ammonia).

$$Sb_4O_6 + 4NaOH = 4NaSbO_2 + 2H_2O$$

The corresponding thio-antimonites are formed when antimony sulphide is dissolved in yellow ammonium sulphide.

$$Sb_2S_3 + 3(NH_4)_2S = 2(NH_4)_3SbS_3$$

Thio-antimonates (e.g. $Na_3SbS_4$) can also be prepared, although the corresponding sulphide ($Sb_2S_5$) is unknown.

## Determination of Antimony

Antimony is determined volumentrically (as in the official assays of Sodium and Potassium Antimonyl Tartrates) by oxidizing tervalent antimony compounds to the quinquevalent state by means of iodine. As in the case of the corresponding arsenic determination, the oxidation is reversible, and proceeds only to completion in neutral solution. Excess sodium bicarbonate is added before titrating. In the assay of Stibophen, a back titration method, based on the same reaction, is used.

## BISMUTH

Bismuth is found in the metallic state. Native bismuth contains antimony and arsenic. It is purified by melting under potassium nitrate, which oxidizes the other metals to arsenate and antimonate. Precipitated Bismuth B.P. is obtained by reduction of an acid solution of bismuth chloride by hypophosphorous acid.

$$3H_3PO_2 + 4BiCl_3 + 6H_2O = 3H_3PO_4 + 12HCl + 4Bi$$

Bismuth is a heavy lustrous metal, which crystallizes in hollow cubes. It has a low melting point, and is an important constituent of low melting alloys.

Bismuth is not a reactive metal. It burns when heated in air, and dissolves in nitric acid to form the nitrate. Bismuth hydride has only been obtained in traces. Bismuth is tervalent in its more important compounds, but some compounds of bismuth are known in which the metal is quinquevalent (e.g. $Bi_2O_5$ and $NaBiO_3$, sodium bismuthate, a powerful oxidizing agent) ).

## Bismuth Sesquioxide ($Bi_2O_3$)

This oxide is basic and does not resemble arsenious and antimonious oxides by dissolving in alkalis. It is obtained by heating the metal in air, or by ignition of bismuth hydroxide, carbonate, or nitrate.

## Other Compounds of Bismuth

Bismuth hydroxide is precipitated by ammonia from solutions of bismuth salts. It is a weak base, and bismuth salts are easily hydrolyzed, e.g. when a solution of bismuth chloride is diluted considerably, a precipitate is obtained of the oxychloride, and on dilution, a solution of bismuth nitrate forms the oxynitrate.

$$BiCl_3 + H_2O = BiOCl + 2HCl$$

$$Bi(NO_3)_3 + 2H_2O = Bi(OH)_2NO_3 + 2HNO_3$$

The precipitates obtained when bismuth nitrate reacts in solution with sodium carbonate or sodium salicylate are basic salts of rather indefinite composition. Their approximate compositions are represented by the respective formulae

$$2[(BiO)_2CO_3]H_2O \text{ and } C_6H_4(OH)COO(OBi)$$

Correspondingly the action of gallic acid on bismuth hydroxide yields an indefinite subgallate. The bismuth compounds corresponding to the alkali metal antimonyl tartrates are also of indefinite composition.

The solution obtained by dissolving bismuth iodide in potassium iodide solution contains a complex salt. It is used as an alkaloidal reagent (p. 576).

$$KI + BiI_3 = KBiI_4$$

## Control of Purity of Bismuth Compounds

Owing to the ease with which basic bismuth salts are precipitated from weakly acid solutions, many of the ordinary limit tests cannot be applied to bismuth compounds. A special series of official tests has been devised.

*Test for Lead and Copper*

The compounds are dissolved in nitric acid (after a preliminary ignition to remove organic matter when necessary), and most of the bismuth is removed by diluting considerably with water. The precipitated basic bismuth nitrate is removed by filtration, and after a further concentration by evaporation and a second filtration, portions of the filtrate are tested for lead with dilute sulphuric acid (lead sulphate is insoluble) and for copper with ammonia. In this case, a white precipitate is obtained from the remaining bismuth, but no blue colour due to cuprammonium compounds should be observed.

*Test for Sulphate*

Barium chloride is added to a solution in moderately concentrated hydrochloric acid (after removing, in the case of the salicylate, the precipitated salicylic acid by filtration). The limit test for chloride in Bismuth Salicylate is also carried out in strongly acid (nitric acid) solution after removing the precipitated salicylic acid.

*Test for Silver*

The substance is dissolved in concentrated hydrochloric acid (after a preliminary ignition in the case of the salicylate, etc.). No precipitate is formed as silver chloride is slightly soluble in concentrated hydrochloric acid, but as silver iodide is insoluble in this acid, a precipitate is obtained on the addition of potassium iodide.

*Test for Alkali and Alkaline Earth Metals*

The substance is boiled with acetic acid. The bismuth salts are not very soluble, but the more soluble alkali and alkaline earth metal salts are dissolved. The solution is filtered, and any dissolved bismuth, lead, and copper are removed by precipitation with hydrogen sulphide. The solution is then evaporated to dryness and ignited with sulphuric acid. The residue of sulphates is weighed.

### *Test for Nitrates*

(The compounds are prepared from bismuth nitrate.) The test depends on the oxidation of indigo carmine solution by nitrates in the presence of sulphuric acid. For Bismuth Salicylate, a special test is used, which depends on the formation of a pink colour when a solution of a salicylate containing a trace of nitrate is superimposed on concentrated sulphuric acid (nitrosalicylic acid is formed), while for Bismuth Subgallate the ordinary "brown-ring" test with ferrous sulphate is used.

## Determination of Bismuth

Bismuth is determined gravimetrically by precipitation with ammonium phosphate in weakly acid solution. After filtration and ignition, the bismuth is weighed as bismuth phosphate ($BiPO_4$).

$$Bi(NO_3)_3 + (NH_4)_2HPO_4 = BiPO_4 + 2NH_4NO_3 + HNO_3$$

Although there is no official assay for Bismuth Carbonate, Salicylate, and Subgallate, their compositions are controlled by the amount of bismuth oxide left when they are ignited, with nitric acid present when necessary, to destroy organic matter.

# CHAPTER XIII

# CARBON, SILICON, AND BORON

## CARBON

Carbon is one of the less important constituents of igneous rocks, where it occurs mainly in the elementary form as diamond or graphite. It is a much more important constituent of sedimentary rocks, many of which are composed almost entirely of carbonates of calcium or magnesium. Carbon dioxide is present in the air.

Carbon is the chief element present in living tissues. Its compounds with hydrogen, oxygen, nitrogen, and phosphorus constitute the "organic" branch of chemistry (p. 317). A very large number of these organic compounds have been obtained from living sources, and many others have been prepared in the laborarory. These compounds contain chains or rings of carbon atoms. In its ability to form such chains or rings, carbon differs from all the other elements in a very marked manner.

Elementary carbon exists in two crystalline forms (diamond and graphite), and one amorphous form (charcoal).

*Diamonds* are found in the "blue earth" of South Africa. It has been claimed that small diamonds have been obtained artificially by rapid cooling under pressure of solutions of carbon in molten iron or certain silicates.

Diamonds crystallize in octahedra. They are very hard and possess a high refractive index (qualities which render them valuable as gem-stones). At a high temperature, diamonds are converted into graphite. The analysis of the crystal structure of the diamond by means of X-rays shows that each carbon atom is united to four others situated at the corners of a regular tetrahedron, at the centre of which is placed the first carbon atom (Fig. 22). As every carbon atom in the crystal is linked similarly, the whole crystal may be regarded as a gigantic single molecule. (In this connexion, the difference in the melting points of carbon and its neighbours in the Periodic Table is very striking: Carbon, m.p. above 3,000°C;

Nitrogen, m.p. $-210°C$; oxygen, m.p. $-227°C$; fluorine, m.p. $-223°C$.) The tetrahedral arrangement of carbon atoms which is found in the diamond is similar to the arrangement of radicles about carbon which is found in the *aliphatic* derivatives of organic chemistry.

*Graphite* is found as a mineral. It is manufactured by heating anthracite in an electric furnace, when the heat drives out the more volatile impurities and crystallizes the carbon. Graphite crystallizes in soft black crystals, which conduct electricity. It vaporizes without melting in the electric arc.

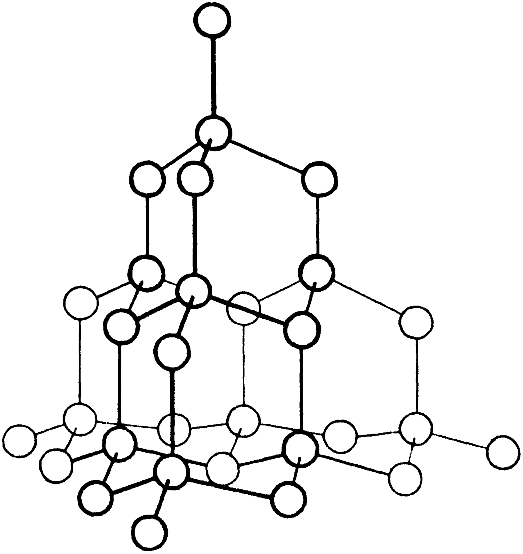
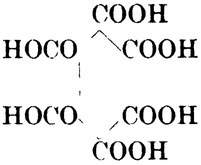


FIG. 22. CRYSTAL STRUCTURE OF DIAMOND

Graphite seems to be more stable than the diamond, for on heating, the latter substance changes into graphite. Graphite is used as a lubricant, its lubricating action being dependent on its crystal structure. Graphite crystals are made up of a series of sheets, which slide over one another fairly freely (Fig. 23). The carbon atoms constituting these sheets are arranged in the form of hexagonal rings in close contact (fused hexagonal rings), so that graphite is closely related to the *aromatic* derivatives of organic chemistry. On oxidation graphite yields aromatic acids, such as mellitic acid.



*Charcoal* is obtained by the partial combustion or destructive distillation of wood, when the more volatile constituents are driven off. Charcoal is very porous, and it possesses strong adsorptive properties. The adsorptive power of charcoal is increased if the charcoal has been *activated* by heating it for several hours in steam, or in air at 800°C. Charcoal adsorbs gases very strongly (more strongly at the temperature of liquid air), and it is used commercially to recover organic solvent vapours, e.g. in the rubber industry. It also adsorbs many colouring matters and dyes, and it is therefore used to decolorize and clarify many liquids, e.g. sugar solutions (p. 462).

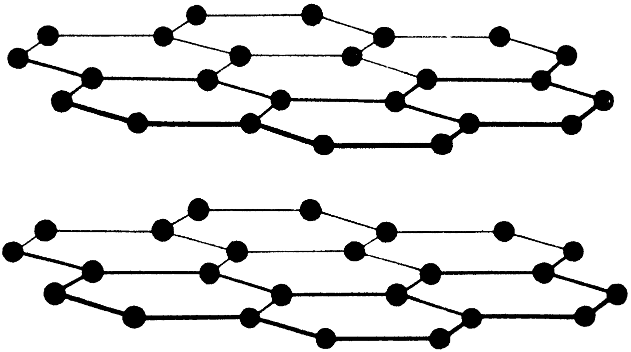


FIG. 23. CRYSTAL STRUCTURE OF GRAPHITE

Chemically, charcoal is more reactive than graphite. It burns at a lower temperature. Its fundamental structure resembles that of graphite, but it contains small quantities of hydrogen. The same basic graphite structure is also present in coal.

## Chemical Properties of Carbon

Carbon is not a very reactive element. It burns in air, forming carbon monoxide and carbon dioxide. At high temperatures, it is a strong reducing agent, and it is used to remove oxygen from metallic oxides in the smelting of metal ores.

$$ZnO + C = Zn + CO$$

Carbon combines directly with sulphur, and with hydrogen at high temperatures (to form small quantities of hydrocarbons). It does not react with chlorine, and graphite electrodes are therefore used in electrolytic apparatus generating chlorine. Carbon combines with some metals. Calcium carbide is important as the source of acetylene. Iron carbide ($Fe_3C$) is sometimes present in cast iron and steel.

For the compounds of carbon with hydrogen and with the halogens, see organic section (pp. 318: 337).

### OXIDES OF CARBON

Carbon forms two important oxides, carbon monoxide (in which carbon is bivalent), and carbon dioxide (in which carbon is quadrivalent). Other oxides have been obtained by dehydrating organic acids, e.g. $C_3O_2$, malonic anhydride.

## Carbon Monoxide

Carbon monoxide is obtained commercially (as a constituent of various fuel gases) by the action of air or steam on heated carbon.

$$2C + O_2 = 2CO$$
$$C + H_2O = CO + H_2$$

It is also obtained by the reduction of carbon dioxide by carbon, and during the reduction of metal ores by carbon.

$$CO_2 + C = 2CO$$
$$3C + Fe_2O_3 = 2Fe + 3CO$$

The gases obtained as above are burnt directly as fuels. It is not practicable to separate pure carbon monoxide from them.

Pure carbon monoxide is obtained in the laboratory by removing the elements of water from formic acid or oxalic acid. (With the latter substance carbon dioxide is also formed and must be removed by passing the evolved gases through potassium hydroxide solution.)

$$H_2CO_2 = H_2O + CO$$
$$H_2C_2O_4 = H_2O + CO + CO_2$$

The dehydration is usually carried out by heating the sodium salt of the acid with sulphuric acid.

Carbon monoxide is a very poisonous gas. It is less soluble and less easily condensed than carbon dioxide. In its chemical properties carbon monoxide behaves as an unsaturated compound (cf. p. 331). It burns in air with a characteristic blue flame, and it is a powerful reducing agent especially at high temperatures. Small quantities of carbon monoxide may be determined by its reducing action on iodine pentoxide (cf. limit of carbon monoxide in Nitrous Oxide, p. 192).

$$2CO + O_2 = 2CO_2$$
$$CO + CuO = Cu + CO_2$$
$$I_2O_5 + 5CO = I_2 + 5CO_2$$

Carbon monoxide readily forms addition products with chlorine and with many metals.

$$CO + Cl_2 = COCl_2$$
$$4CO + Ni = \underset{\text{Nickel carbonyl}}{Ni(CO)_4}$$

Under special conditions it is absorbed by alkalies (to form formates). It is readily absorbed by ammoniacal cuprous chloride solution (to form an addition compound, possibly $Cu_2Cl_2$, CO, $2H_2O$). In gas analysis, carbon monoxide is usually determined by absorption in ammoniacal or acid cuprous chloride solution, as, for example, its detection in the residual gas after absorption of the ethylene and oxygen in the assay of Ethylene B.P.

Carbon monoxide combines with the haemoglobin of the blood to form a bright red substance which possesses a characteristic absorption spectrum. This compound is very stable, and blood containing carbon monoxide keeps its bright red colour on standing exposed to air for several months. Further, this blood gives a red precipitate with pyrogallol and tannic acid, while normal blood gives a greyish brown precipitate. The official test for the presence of carbon monoxide in Carbon Dioxide and in Ethylene depends on the reaction with haemoglobin.

The unsaturated nature of carbon monoxide is in agreement with the formula C=O, in which carbon is bivalent. Other compounds containing bivalent carbon are known (cf. the isocyanides, p. 436), all of which, like carbon monoxide, are very poisonous.

### Gaseous Fuels

The most important gaseous fuels are (1) coal gas obtained from the destructive distillation of coal, (2) water gas, (3) producer gas, (4) blast furnace gases containing carbon monoxide,

$$3C + Fe_2O_3 = 2Fe + 3CO,$$

(5) natural gas (p. 324), an important fuel locally.

*Coal Gas.* The gas obtained when coal is destructively distilled (i.e. heated to a red heat out of contact with air) consists chiefly of hydrogen and methane. Liquid products are also collected: (*a*) an aqueous liquid containing ammonia, (*b*) a tarry liquid which is an important source of certain organic substances (p. 487). The residue in the retort consists of coke.

Coal gas is purified by scrubbing with water (to remove the last traces of ammonia) and by passing over lime and oxide of iron [which remove the hydrogen sulphide and hydrogen cyanide (p. 228) present in the gas]. After the iron oxide has become saturated with hydrogen sulphide, it is revived by exposure to air. It can then be used again until it contains nearly half its bulk of sulphur. It then becomes a valuable source of sulphur and cyanogen compounds.

$$Fe_2O_3 + 3H_2S = Fe_2S_3 + 3H_2O$$

$$2Fe_2S_3 + 3O_2 = 2Fe_2O_3 + 6S$$

Carbon disulphide, which is also present in crude coal gas, is not absorbed by the iron oxide unless it is first reduced to hydrogen sulphide by passing the gas over a heated nickel catalyst.

$$CS_2 + 4H_2 = 2H_2S + CH_4$$

The luminosity of coal gas is mainly due to its ethylene and benzene constituents. The compositions of the gas and the liquid products vary considerably with the temperature at which the coal is distilled. In the low temperature carbonization process, the temperature is arranged so that a considerable quantity of the more volatile liquid hydrocarbons are obtained so that they may be extracted for use as a motor fuel.

*Producer Gas* is obtained by passing a limited supply of air through burning carbon.

$$C + O_2 = CO_2$$

$$CO_2 + C = 2CO$$

It consists mainly of carbon monoxide and nitrogen.

*Water Gas*, which consists of a mixture of hydrogen and carbon monoxide, is obtained by passing steam over red hot carbon.

$$C + H_2O = CO + H_2$$

Water gas is used as a source of hydrogen. (The carbon monoxide is removed by passing the gases mixed with more steam over a catalyst, whereby carbon dioxide is formed and this gas can be removed by liquefying or dissolving in water.)

$$CO + H_2O = CO_2 + H_2$$

Water gas is also converted into methane, methyl alcohol, or other organic compounds by passing it over the appropriate catalysts at different temperatures.

$CO + 3H_2 = CH_4 + H_2O$ (nickel catalyst, 240 C, atmospheric pressure)

$CO + 2H_2 = CH_3OH$ (zinc oxide|chromium oxide catalyst, 380 C, high pressure)

One disadvantage of water gas as a fuel gas is that it can only be made intermittently. The reaction of steam with carbon is an endothermic reaction.

$$C + H_2O = CO + H_2 - 29{,}000 \text{ cal.}$$

Consequently, the temperature of the heated carbon falls during the conversion to water gas, so that it is necessary to stop the conversion, and raise the temperature again.

The formation of producer gas by passing air over heated carbon takes place with the evolution of heat.

$$2C + O_2 = 2CO + 58{,}000 \text{ cal.}$$

Consequently it is often found convenient to use a mixture of steam and air in such a ratio that the heats of reaction compensate one another and the temperature of the heated mass is kept constant. The product which is then obtained (semi-water gas) contains nitrogen (52 per cent), carbon monoxide (27 per cent), and hydrogen (14 per cent) with small quantities of other gases.

## Carbon Dioxide and Carbonic Acid

Carbon dioxide is prepared in the laboratory by the action of an acid on a carbonate (e.g. marble and hydrochloric acid).

$$CaCO_3 + 2HCl = CaCl_2 + H_2O + CO_2$$

On a large scale it is obtained from four sources: (1) during the burning of limestone (p. 254), (2) by combustion of coke, etc., in air, (3) as a by-product of the brewing industry (cf. p. 355), (4) as a by-product of the Haber process for the fixation of nitrogen (p. 186). Carbon dioxide is condensed into cylinders after drying with sulphuric acid.

The carbon dioxide obtained from the burnt gases of coke, etc., may contain sulphur dioxide or carbon monoxide. The official test for the former gas depends on its acidity, the gas being passed through an unbuffered methyl orange solution, both with and without previously passing through sodium bicarbonate, which absorbs sulphur dioxide. The carbon monoxide test is made with haemoglobin. The gas obtained during fermentation may contain reducing substances which may be detected by their action on ammoniacal silver nitrate solution, which also would detect hydrogen sulphide and phosphine.

Carbon dioxide is a heavy gas, which is easily liquefied (critical temperature 31° C). On rapid evaporation, liquid carbon dioxide becomes so cold that it freezes, forming "carbon dioxide snow," which is sold for use in refrigerators and cold storage plants.

Carbon dioxide is slightly soluble in water. The solution is weakly acidic and probably contains carbonic acid. The carbon dioxide is removed completely from the solution by boiling.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

Carbonic acid is a dibasic acid and forms two series of salts, the normal carbonates (insoluble, except in the case of the alkali metals) and the bicarbonates (soluble).

Carbonates may be prepared by the reaction of carbon dioxide on the corresponding hydroxide or oxide, or in the case of an insoluble carbonate by double decomposition from a soluble carbonate.

$$2NaOH + CO_2 = Na_2CO_3 + H_2O$$

$$CaCl_2 + Na_2CO_3 = CaCO_3 + 2NaCl$$

Bicarbonates are formed when carbon dioxide is passed into a solution or suspension of a carbonate.

$$CaCO_3 + H_2O + CO_2 = Ca(HCO_3)_2$$

(For the manufacturing process for sodium bicarbonate, see p. 246.)

The normal carbonates of strong bases are alkaline in reaction, the bicarbonates of strong bases are almost neutral. The carbonates of the weaker bases are easily hydrolyzed with the formation of basic carbonates. Very weak bases do not form carbonates. The alkali metal bicarbonates may be distinguished from the corresponding carbonates as they do not give precipitates with magnesium sulphate (magnesium bicarbonate is soluble in water). On gentle heating, bicarbonates are converted to carbonates with loss of carbon dioxide. The carbonates of all the metals except the alkali metals are decomposed on heating.

$$CaCO_3 - CaO + CO_2$$

DETERMINATION OF CARBONATES AND BICARBONATES

The volumetric determination of carbonates and bicarbonates is based on the displacement of the weak carbonic acid by stronger acids.

$$Na_2CO_3 + 2HCl = 2NaCl + H_2O + CO_2$$

Carbonic acid is a weak acid, a saturated solution of carbon dioxide having a $p$H value of 4·5, and therefore it does not react acid to methyl orange. Soluble bicarbonates and carbonates can be determined by direct titration, using methyl orange as indicator. Insoluble carbonates can be determined by dissolving in excess acid and back titrating with standard alkali.

The official assay of Carbon Dioxide depends on its absorption in potassium hydroxide solution.

DERIVATIVES OF CARBONIC ACID

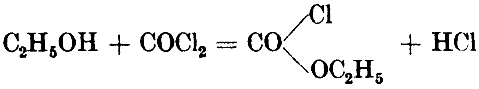
*Carbonyl Chloride.* The acid chloride of carbonic acid is carbonyl chloride or phosgene ($COCl_2$). This substance is prepared by the union of carbon monoxide with chlorine, or by the action of fuming sulphuric acid on carbon tetrachloride.

$$CO + Cl_2 = COCl_2$$

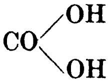
$$CCl_4 + 2SO_3 = COCl_2 + S_2O_5Cl_2$$

Phosgene is a colourless gas, which is very poisonous. It has been found to be a dangerous decomposition product of chloroform (cf. p. 345). Phosgene is hydrolyzed by water forming hydrochloric acid and carbonic acid, and reacts with alcohol to form ethyl chlorocarbonate.

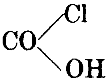
$$COCl_2 + H_2O = CO_2 + 2HCl$$



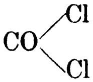
Chlorocarbonic acid is intermediate in structure between carbonic acid and carbonyl chloride.



Carbonic acid

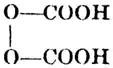


Chlorocarbonic acid



Carbonyl chloride

*Percarbonic Acid.* When a solution of potassium carbonate is electrolyzed, potassium percarbonate is obtained. This is a salt of percarbonic acid ($H_2C_2O_6$).



$$\begin{array}{l} O{-}COOH \\ | \\ O{-}COOH \end{array}$$

## OTHER COMPOUNDS OF CARBON

### Compounds of Carbon and Sulphur

The most important compound of carbon and sulphur is carbon disulphide ($CS_2$) (corresponding to carbon dioxide).

Carbon disulphide is obtained when a mixture of carbon and sulphur is heated to a high temperature in an electric furnace.

$$C + 2S = CS_2$$

Carbon disulphide is a volatile inflammable liquid. It is a good solvent for sulphur and many organic substances.

### Compounds of Carbon and Nitrogen

Many organic compounds contain nitrogen. In this section the inorganic compounds containing the cyanogen radical (CN) are described.

The cyanogen radical is univalent, and in many ways behaves like a single atom of a halogen [cf. Na(CN) and NaCl;

$(CN)_2$ and $Cl_2$]. It was one of the first known examples of a compound radical.

Cyanogen compounds are prepared from nitrogenous organic matter, from the spent oxide of the gas works, or by fixing the nitrogen of the air. The first two sources yield ferrocyanides (p. 296), and the simpler cyanides are obtained from them by heating alone or with metallic sodium.

$$K_4Fe(CN)_6 = 4KCN + Fe + 2C + N_2$$

$$K_4Fe(CN)_6 + 2Na = 4KCN + 2NaCN + Fe$$

Nitrogen from the air is converted into cyanides by two methods—

(1) By the action of red hot carbon on sodamide formed by passing ammonia over molten sodium.

$$2Na + 2NH_3 = 2NH_2Na + H_2$$

$$NaNH_2 + C = NaCN + H_2$$

(2) When calcium carbide is heated in an atmosphere of nitrogen and the product is fused with sodium carbonate, sodium cyanide is formed.

$$CaC_2 + N_2 = \underset{\text{Calcium cyanamide}}{CaCN_2} + C$$

$$CaCN_2 + C + Na_2CO_3 = CaCO_3 + 2NaCN$$

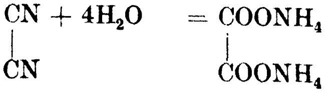
*Cyanogen* ($C_2N_2$) is obtained when mercuric cyanide is heated.

$$Hg(CN)_2 = Hg + (CN)_2$$

It is a poisonous gas, which dissolves in water. Chemical reactions take place when its solution is allowed to stand.

$$(CN)_2 + H_2O = HCN + HCNO$$

$$(\text{cf. } Cl_2 + H_2O = HCl + HClO)$$



$$\begin{matrix} CN \\ | \\ CN \end{matrix} + 4H_2O = \begin{matrix} COONH_4 \\ | \\ COONH_4 \end{matrix}$$

(cf. organic nitriles, p. 435)

$$HCN + 2H_2O = HCOONH_4$$

*Hydrogen Cyanide* is obtained by distilling a cyanide or ferrocyanide with dilute sulphuric acid. The anhydrous gas can be prepared by heating potassium cyanide with potassium hydrogen sulphate.

$$2KCN + H_2SO_4 = K_2SO_4 + 2HCN$$
$$KCN + KHSO_4 = K_2SO_4 + HCN$$

Hydrogen cyanide is a very poisonous gas which possesses a characteristic odour which, however, many people are incapable of detecting. It is easily condensed to a liquid (b.p. 26°C). It is soluble in water giving a solution which is only faintly acid (hydrocyanic acid). The cyanides are hydrolyzed in solution. Their solutions give an alkaline reaction and smell strongly of hydrocyanic acid. Weak acids (even carbon dioxide) displace hydrocyanic acid from its salts.

$$HCl + KCN = HCN + KCl$$

The weakness of hydrocyanic acid is in marked contrast to the strength of the acids formed by the hydrogen halides.

The cyanides differ from the chlorides in their tendency to form complex cyanides in which the metal enters into the acid radical.

$$Fe(CN)_2 + 4KCN = K_4Fe(CN)_6 \text{ (cf. p. 296)}$$
$$2KCN + Cu(CN)_2 \quad K_2Cu(CN)_4$$
$$KCN + AgCN = KAg(CN)_2$$

Many of these complex cyanides are stable, so that many metals do not respond to their ordinary tests in presence of potassium cyanide (cf. limit test for lead, p. 128).

Cyanides also differ from the halides in their reaction with concentrated sulphuric acid. The cyanogen radical is destroyed and carbon monoxide is evolved.

$$2KCN + H_2SO_4 = 2HCN + K_2SO_4$$
$$2HCN + 4H_2O = 2HCOONH_4{}^*$$
(cf. organic nitriles, p. 435)

$$2HCOONH_4 + H_2SO_4 = (NH_4)_2SO_4 + 2H_2O + 2CO$$
$$2KCN + 2H_2SO_4 + 2H_2O = K_2SO_4 + (NH_4)_2SO_4 + 2CO$$

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* As the reverse of this reaction, hydrogen cyanide is obtained when ammonium formate is heated with a dehydrating agent (phosphoric oxide).

Chlorine, bromine and iodine react on potassium cyanide to form the poisonous cyanogen halides

$$Cl_2 + KCN = KCl + CNCl$$

*Formula of Hydrogen Cyanide.* Two sets of organic derivatives, the cyanides and the isocyanides (pp. 435, 436), may be obtained from metallic cyanides.

$$CH - C \equiv N$$

Methyl cyanide
(corresponding to $H - C \equiv N$)

$$CH_3 - N = C$$

Methyl isocyanide
(corresponding to $H - N = C$)

Hydrogen cyanide is probably represented by both formulae, i.e. it is a tautomeric equilibrium mixture (p. 471) containing both substances.

$$H - C \equiv N \rightleftharpoons H - N = C$$

It can be shown that only a small proportion is in the isocyanide form in liquid hydrogen cyanide.

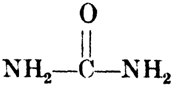
*Cyanic Acid* (HCNO). Potassium cyanide is a strong reducing agent, and it absorbs oxygen to form potassium cyanate, e.g. when heated with lead oxide.

$$KCN + PbO = KCNO + Pb$$

Ammonium cyanate is of interest by reason of its conversion into urea (p. 440).

$$NH_4 - C \equiv N = O$$

Ammonium cyanate



$$NH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

Urea

*Thiocyanic Acid* corresponds to cyanic acid in which the oxygen has been replaced by sulphur. Potassium cyanide reacts with sulphur on heating to form potassium thiocyanate.

$$KCN + S = KCNS$$

Ammonium thiocyanate is obtained as a by-product in the purification of coal gas. It can be prepared by reacting on carbon disulphide with a concentrated solution of ammonia.

$$CS_2 + 4NH_3 = NH_4CNS + (NH_4)_2S$$

Ferric thiocyanate [$Fe(CNS)_3$] has a deep red colour, which is used to detect the presence of thiocyanates and ferric compounds.

## Determination of Carbon and Hydrogen in Organic Compounds

Carbon and hydrogen in organic compounds are determined by quantitative oxidation. In the usual method, the substance is mixed with copper oxide and heated in a current of oxygen. The carbon dioxide and water formed are absorbed and weighed in tubes containing soda-lime and calcium chloride respectively. When the organic compounds contain elements other than carbon, hydrogen and oxygen, the gases, before absorption must be passed over a silver spiral (to remove halogens or sulphur) or over a heated copper spiral (to reduce nitrogen oxides to nitrogen which is not absorbed by the soda-lime).

## SILICON

Although silicon resembles carbon in being quadrivalent, its properties and those of its compounds are very different from those of carbon and the corresponding carbon compounds (cf. carbon dioxide and silica). Silicon is the most important element in the mineral world, as carbon is in the organic world, silicon oxide ($SiO_2$) making up 60 per cent of the solid fraction of the earth's crust.

Silicon is obtained either by reduction of silicon tetrachloride by heating it with sodium, or by reducing silica by heating it with aluminium. The product is amorphous silicon, but a form possessing a metallic lustre and slight conductivity is obtained when silica is reduced with carbon in an electric furnace.

$$4Na + SiCl_4 \overset{\text{heat}}{=} 4NaCl + Si$$

$$4Al + 3SiO_2 \overset{\text{heat}}{=} 3Si + 2Al_2O_3$$

$$2C + SiO_2 \overset{\text{electric furnace}}{=} 2CO + Si$$

Silicon is a reactive element which combines readily with oxygen, chlorine, and carbon.

$$Si + O_2 = SiO_2$$

$$Si + 2Cl_2 = SiCl_4$$

$$C + Si = CSi$$

Some metals combine with silicon to form silicides. Ferrosilicon, which is obtained by reduction of siliceous iron ores and is important in the steel industry, contains the compound FeSi.

Silicon does not react with acids, but it dissolves in alkalis liberating hydrogen and forming silicates.

$$Si + 2NaOH + H_2O = Na_2SiO_3 + 2H_2$$

## Compounds of Silicon

Silicon combines with hydrogen to form hydrides ($SiH_4$ and $Si_2H_6$; compare methane $CH_4$ and ethane $C_2H_6$).

Silicomethane is obtained when magnesium silicide dissolves in dilute acid.

$$Mg_2Si + 4HCl = 2MgCl_2 + SiH_4$$

It is a gas which burns readily in air or in chlorine.

$$SiH_4 + 2O_2 = SiO_2 + 2H_2O$$

$$SiH_4 + 4Cl_2 = SiCl_4 + 4HCl$$

The formulae of the compounds of silicon with the halogens correspond with those of the carbon halogen compounds, thus: silicon tetrafluoride $SiF_4$, silicon tetrachloride $SiCl_4$, silicochloroform $SiHCl_3$. Many other silicon compounds of organic type have achieved industrial importance, e.g. in the manufacture of non-inflammable plastics and rubber substitutes.

SILICON TETRAFLUORIDE is obtained by the action of hydrofluoric acid on silica or silicates.

$$4HF + SiO_2 = SiF_4 + 2H_2O$$

It is prepared by heating a mixture of calcium fluoride and silica with concentrated sulphuric acid.

$$2CaF_2 + 2H_2SO_4 + SiO_2 = SiF_4 + 2CaSO_4 + 2H_2O$$

Silicon tetrafluoride is a gas which is readily hydrolyzed by water forming silicic and hydrofluoric acids.

$$SiF_4 + 3H_2O = 4HF + H_2SiO_3$$

Silicon tetrafluoride forms the complex fluorosilicic acid by reaction with hydrogen fluoride.

$$2HF + SiF_4 = H_2SiF_6$$

Fluorosilicic acid is the chief product obtained when silicon tetrafluoride reacts with water.

$$3SiF_4 + 3H_2O = 2H_2SiF_6 + H_2SiO_3$$

Silicon tetrachloride is also hydrolyzed by water, but as it does not combine with hydrogen chloride the final products are hydrochloric acid and silicic acid.

$$SiCl_4 + 3H_2O = 4HCl + H_2SiO_3$$

## Silica

The most important compound of silicon is the oxide silica ($SiO_2$). Free silica exists as quartz (rock crystal) in igneous rocks, and in sands derived from them by the removal of the less stable constituents of the rocks. Amorphous silica deposits are also found (e.g. flint; agate).

Silica melts at very high temperatures forming a viscous liquid, which on cooling sets to a glass. Silica glass is an important commercial product. It is very resistant to attack by acids, so that it is used in the construction of chemical plant. It has a low coefficient of thermal expansion and does not crack when exposed to sudden changes in temperature. Like quartz, it is transparent to ultra-violet and infra-red light.

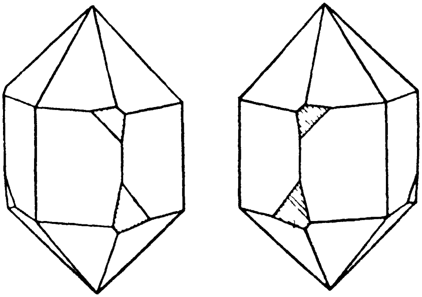

(a) Right-handed (b) Left-handed

FIG. 24. CRYSTALS OF QUARTZ

Crystalline silica (of which quartz is the most important form) is very hard. Quartz crystals are optically active, both dextro-rotatory and laevo-rotatory quartz being found in nature (Fig. 24). (The silica molecules are arranged spirally in the crystals.)

Silica is an acidic oxide. It is insoluble in water and acids (except hydrofluoric acid), but dissolves readily in alkalis forming silicates.

$$SiO_2 + 2NaOH = Na_2SiO_3 + H_2O$$

When sodium silicate solution is acidified a jelly-like precipitate of silicic acid is obtained. Often this remains in colloidal solution, from which it may be coagulated by the addition of salts.

$$Na_2SiO_3 + 2HCl = 2NaCl + H_2SiO_3$$

### SILICATES

The simpler silicates are derived from metasilicic acid ($H_2SiO_3$) and orthosilicic acid ($H_4SiO_4$), but more complex silicates are found as minerals.

Silicates are manufactured artificially by dissolving silica in caustic alkalis (water-glass), or by fusing silica with various metallic salts whereby the non-volatile silica replaces the more volatile acids.

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$$

*Glass* consists of the silicates of calcium and sodium (with additions in special cases of potassium, lead, barium, and zinc silicates and borates). These silicates melt to form very viscous liquids. On cooling they solidify gradually to clear glasses (really a supercooled liquid, which in course of time may crystallize when the glass becomes "devitrified," brittle and no longer clear). In the manufacture of glass, sand is heated with the carbonates of the various metals in the required proportion (sodium is often added as the cheaper nitrate or sulphate). The green colour of glass, due to the presence of ferrous silicates, is removed by the addition of manganese dioxide to the molten mass to oxidize the ferrous iron. Many glasses used nowadays for heat-resisting vessels contain free silica and are thus intermediate in composition between an ordinary glass and a pure silica glass.

The relative proportions of the constituents control the properties of the glass, e.g. the slight solubility in water and the resistance to attack by acids or alkalis.

### *Official Test for Alkalinity of Glass*

The alkalinity of glass is controlled using a solution of methyl red whose *p*H value has been adjusted by adding dilute hydrochloric acid to correspond with the beginning of the change in colour of the indicator from red to yellow (*p*H 4·2). After testing with the glass, the alkali derived therefrom should not be sufficient to alter the *p*H value of this solution (unbuffered) to that of the full yellow of methyl red (*p*H 6·4). $10^{-4 \cdot 2} - 10^{-6 \cdot 4} = 0 \cdot 000156$ gramme-equivalents of hydrogen ions per litre are necessary to effect this change.

Two types of test are recognized in the *British Pharmacopœia*—

(1) Test on powdered glass;
(2) Test on whole ampoules.

*The test on powdered glass* is carried out on glass which will pass through a No. 25 but not a No. 36 sieve. It is washed free from dust with alcohol and then dried.

The resistant glass apparatus in which the test is carried out is first tested by boiling with the methyl red solution (under a reflux condenser) in a water bath for one hour. At the end of that time no perceptible colour change in the indicator should be observed. 5 g. of powdered glass are then boiled under similar conditions for half an hour with 100 mils of the acidified methyl red solution. The indicator should not have changed to its full yellow colour. (If necessary an alkaline solution of methyl red can be used as a comparison.)

In *the test on whole ampoules* at least six ampoules must be used and each must pass the test. They are filled with the acid methyl red solution and heated in steam in an autoclave at a pressure of 15 lb. per in.$^2$ for half an hour. The solution in each ampoule should not have changed to the full yellow colour. (In the case of coloured ampoules, the solution must be removed on to a clean white tile for examination.)

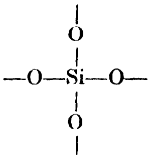
Ampoules which have once passed the test may fail to do so after storage. It is desirable that they should be retested before using if they have been stored for more than a fortnight since their last test. If they fail to pass this test they may be rinsed inside with 5 per cent acetic acid, and then three times with water. If they now pass the test, the whole batch may be used after each ampoule has been washed in the same manner.

## MINERAL SILICATES

Molten igneous masses are usually regarded as solutions of silica with the oxides of the various metallic constituents. On crystallizing, the metallic oxides combine with silica and alumina to form silicates and aluminosilicates. In these compounds (many of which are very complex) silica molecules unite with other silica molecules to form long chains, rings, etc. The linkages of the silica molecules are always made through oxygen (i.e. there is no direct linkage between two silicon atoms) thus:

$$\text{—O—Si—O—Si—O—Si—O—Si—O—}$$

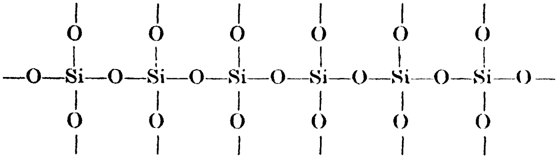
By analysis of crystals of various minerals by means of X-rays, it was shown that every silicon atom is surrounded tetrahedrally by four oxygen atoms, i.e. mineral silicate crystals are composed of the following unit group, here written as if the atoms were lying in one plane.



$$\begin{array}{c} | \\ \text{O} \\ | \\ \text{—O—Si—O—} \\ | \\ \text{O} \\ | \end{array}$$

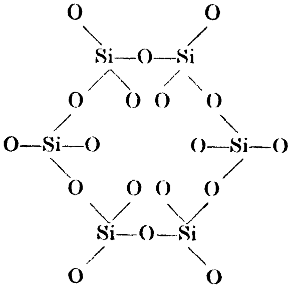
The property of the particular mineral depends on the way in which these units are linked together.* The simplest silicates contain single isolated units, e.g. olivine ($Mg_2SiO_4$); zircon ($ZrSiO_4$).

Fibrous minerals (e.g. asbestos) possess the units linked together in the form of a long chain, thus—



$$\begin{array}{ccccccccccccc} & | & & | & & | & & | & & | & & | & \\ & \text{O} & & \text{O} & & \text{O} & & \text{O} & & \text{O} & & \text{O} & \\ & | & & | & & | & & | & & | & & | & \\ \text{—O—} & \text{Si} & \text{—O—} & \text{Si} & \text{—O—} & \text{Si} & \text{—O—} & \text{Si} & \text{—O—} & \text{Si} & \text{—O—} & \text{Si} & \text{—O—} \\ & | & & | & & | & & | & & | & & | & \\ & \text{O} & & \text{O} & & \text{O} & & \text{O} & & \text{O} & & \text{O} & \\ & | & & | & & | & & | & & | & & | & \end{array}$$

The units may be linked together to form closed rings, or sheets thus—



RING

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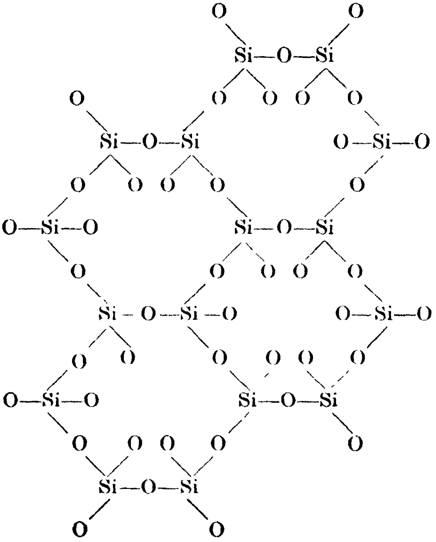
* The different ways in which the silica units are linked in these minerals resemble closely the ways in which carbon atoms may be linked together: (1) single molecules (methane); (2) chains (aliphatic compounds); (3) rings (aromatic compounds); (4) sheets (graphite); (5) complete network (diamond).



SHEET

The substances with sheet molecules are characterized by well-marked cleavages into thin sheets (mica is a typical example). Further, the units may be linked together in all directions so that a complete network is formed, as in quartz and the felspars.

In the aluminosilicates, an aluminium atom replaces a silicon atom in forming the above structures. In all cases, the linkages not occupied in joining two units together are satisfied by the various other metal atoms present in the mineral.

*Clays* consist of minute particles of aluminosilicate minerals derived from the alteration of rocks. Most of the clays form thin flaky particles (sheet type of crystal structure), and the presence of these flaky particles, which are small enough to be of a colloidal nature, gives the clays their characteristic properties. Kaolinite, which is the chief constituent of china clay, has strong adsorptive properties. For use in pharmacy, it is powdered, and freed from gritty matter by elutriation.

*Determination of Silicates.* Silicates are determined as in the official assay of Magnesium Trisilicate, by precipitation as silicic acid followed by ignition to and weighing as silica. In the official assay the first residue is treated with hydrofluoric acid to determine what proportion did not consist of silica.

## BORON

The boron in cooling igneous rocks is liberated, and carried to the surface with the escaping steam as the volatile boric acid. The pools of water formed by the condensation of the steam contain boric acid. Quantities of this substance are separated from the pools found in volcanic regions. It is purified by recrystallization. Natural deposits of borates (chiefly calcium borate, but also sodium borate) are also important sources of boron compounds.

*Boron* is a non-volatile and not very reactive element. It forms with hydrogen a curious series of hydrides in which boron possesses abnormal valencies (e.g. boroethane $B_2H_6$, borobutane $B_4H_{10}$). In these hydrides boron clearly resembles silicon (cf. $Si_2H_6$).

The *halides of boron* are easily hydrolyzed by water. Boron trifluoride resembles silicon tetrafluoride in the readiness with which it forms complex fluoroborates.

$$BF_3 + 3H_2O = H_3BO_3 + 3HF$$
$$BF_3 + HF = HBF_4$$

The most important compounds of boron are derived from the oxide ($B_2O_3$), which is a glassy solid. It is the anhydride of boric acid ($H_3BO_3$).

### Boric Acid

Boric acid is precipitated when a solution of a soluble borate is acidified. Boric acid is obtained from natural borates by decomposition with acid.

$$Na_2B_4O_7 + H_2SO_4 + 5H_2O = Na_2SO_4 + 4H_3BO_3$$

Boric acid is not very soluble in cold water, but it is soluble in hot 90 per cent alcohol (many impurities may be detected by incomplete solubility in 90 per cent alcohol). In the official arsenic limit test on Boric Acid and Borax, the boric acid is retained in solution by the addition of citric acid.

Boric acid is volatile, and distils in steam. It colours the Bunsen flame green. A solution in alcohol burns with a green flame (due to formation of ethyl borate ( $(C_2H_5)_3BO_3$).

Boric acid may be identified by the characteristic brown colour it imparts to turmeric paper. It differs from the brown colour caused by alkalis as it is not destroyed by acids.

Boric acid is a weak acid and its solution is only very feebly acidic to litmus. Its salts are alkaline in reaction, and they may be titrated with strong acids using an indicator indifferent to boric acid.

Although boric acid contains three atoms of hydrogen and forms a triethyl ester, only one of the three hydrogen atoms is replaced readily by metals. Boric acid and sodium carbonate react together on heating to form the metaborate $NaBO_2$. Complex borates are also important. Borax ($Na_2B_4O_7$, $10H_2O$), which is the most important salt, is disodium tetraborate, while the naturally occurring calcium borates are represented by the formula $2CaO, 3B_2O_3$. More complex borates have been obtained. (The formation of these complex acids is a further point of resemblance between boron and silicon. Some borates resemble silicates in forming glasses, and borates are constituents of many special glasses.)

*Borax* is obtained from natural borax deposits, and from the natural boric acid and calcium borates. The latter substances are converted into borax by heating with sodium carbonate or sodium sulphate.

$$2Ca_2B_6O_{11} + 3Na_2CO_3 = 3CaCO_3 + CaO + 3Na_2B_4O_7$$

The borax is dissolved from the residue after heating, and crystallized from water. Its crystals contain ten molecules of water of crystallization.

## Official Assays of Boric Acid and Borax

Boric acid is too weak an acid to be titrated directly with standard alkali, but it combines with certain organic compounds containing two neighbouring hydroxyl groups (such as glycerol or mannitol) to form stronger monobasic complex acids (e.g. glyceroboric acid). The formulae of these complex acids have not yet been established with certainty.

Boric acid may be titrated with standard alkali in presence of glycerol or a similar substance. In presence of glycerol one equivalent of alkali neutralizes one equivalent of boric acid, i.e. as if the reaction were expressed by the equation (which ignores the presence of the glycerol)—

$$NaOH + H_3BO_3 = NaBO_2 + 2H_2O$$

The indicator chosen in the official assay is phenol violet.

Borax may be determined by titration with acid using methyl orange, which is not affected by boric acid. But an additional check on the presence of impurities is obtained if the boric acid set free during this first titration is also determined by adding glycerol and titrating with standard alkali. (In this case, phenolphthalein is used as the indicator, as it would be difficult to see the phenol violet colour change in the presence of the methyl orange added for the first titration.)

$$Na_2B_4O_7 + H_2SO_4 + 5H_2O = Na_2SO_4 + 4H_3BO_3$$

$$4H_3BO_3 + 4NaOH = 4NaBO_2 + 8H_2O$$

It follows from the above equations that one gramme-molecular weight of borax reacts with *two* equivalents of acid, while the boric acid liberated reacts with *four* equivalents of sodium hydroxide in presence of glycerol. The quantity of N/2 alkali required in the second titration should therefore be double the quantity of N/2 acid required for the first titration. The nature of the impurities present (if any) may be deduced from the exact ratio of the two experimental titration values.

*Perboric Acid.* When sodium borate solution is electrolysed, anodic oxidation causes the formation of sodium perborate. The perborates are oxidizing agents and they are used as mild bleaching agents in laundry work.

Perboric acid has the formula $HBO_3$, and is probably a derivative of hydrogen peroxide (H—O—O—B = O).

## CHAPTER XIV

## THE ALKALI METALS

In dealing with the alkali metals, certain general properties of metals should be borne in mind.

### THE METALS

*General Physical Properties.* A typical metal (e.g. copper or silver) differs from a typical non-metal (e.g. sulphur or phosphorus) in the possession of a characteristic metallic lustre and good electrical conductivity. (Only graphite amongst the non-metals possesses any considerable conductivity.) Many metals are hard and strong, and capable of being drawn into wires (*ductile*) or beaten into thin sheets (*malleable*). When liquid, metals are often capable of dissolving one another. When the solutions are cooled *alloys* are obtained. These may contain intermetallic compounds, solid solutions, or simple mixtures of the constituent metals.

*Chemical Properties.* The lower oxides of the metals are usually basic, but non-metallic oxides are acidic. The chemical properties of some elements are intermediate in character between those of typical metals and typical non-metals (e.g. the oxides of arsenic and antimony are amphoteric), so that it is not possible to draw a complete distinction between metals and non-metals by means of their chemical properties.

From theoretical considerations, it seems that metallic lustre and metallic conductivity are due to the presence of free electrons in the metal. This is correlated with the tendency of the metal to form basic oxides, i.e. the tendency to form from positively charged ions.

$$\mathrm{Na} = \mathrm{Na}^{+} + (-)$$

$$\mathrm{Na} + \mathrm{Cl} = \mathrm{Na}^{+} + \mathrm{Cl}^{-}$$

### THE ALKALI METALS

The five elements, lithium, sodium, potassium, rubidium, and caesium are called the alkali metals. They possess similar physical and chemical properties and their compounds resemble one another closely.

The elements are soft lustrous metals of low boiling point and melting point. They are very reactive and tarnish rapidly in air. Their affinity for oxygen is sufficiently great for them to decompose water at ordinary temperatures with liberation of hydrogen. In the case of potassium, rubidium, and caesium the vigour of the reaction causes the hydrogen to inflame.

$$2Na + 2H_2O = 2NaOH + H_2$$

The alkali metals are invariably univalent. Their oxides and hydroxides are strongly basic, and form neutral salts with strong acids. The salts are generally soluble, so that these metals are not precipitated by the general reagents used for the Group separations in qualitative analysis. The salts usually crystallize easily, especially potassium, rubidium and caesium salts which crystallize without water of crystallization. The elements and their compounds are further characterized by the colorations they impart to the Bunsen flame, e.g. lithium, red; sodium, yellow; potassium, lilac. Analysis of these colorations by means of the spectroscope shows the existence of characteristic spectral lines.

Lithium differs to some extent from the other members of the family, and shows some resemblance to the elements in the next group of the Periodic Table. For example, lithium carbonate, phosphate, and fluoride are insoluble in water like the corresponding calcium compounds but unlike the corresponding sodium compounds. Lithium carbonate resembles calcium carbonate in being decomposed into the oxide on heating.

## SODIUM

Sodium is a common element It does not occur in the free state owing to its chemical activity.

The chief commercial source of sodium compounds is common salt derived from salt deposits or sea water. Other sodium salts (such as borax, and Chile saltpetre) are found locally, and are of economic importance for the acid radicle which they contain.

Rock salt is obtained from the salt deposits either by mining, or by dissolving the salt in water and pumping the brine solution to the surface. Sodium chloride can be obtained by evaporation of this solution, but the brine solution is often converted directly into other compounds.

Sea water, and therefore salt deposits, contain, in addition to sodium chloride, magnesium and calcium sulphates and chlorides, and these substances are therefore possible impurities in most sodium compounds. To purify the crude sodium chloride, the brine solution is treated with sodium carbonate, which precipitates the calcium and magnesium as carbonate.

$$MgCl_2 + Na_2CO_3 = MgCO_3 + 2NaCl$$

(A cheaper method of purifying the salt is by passing an electric current through the solution for a short time. A small quantity of sodium hydroxide is formed, which combines with the dissolved carbon dioxide forming sodium carbonate, which then reacts with the calcium and magnesium salts.)

The purer samples of sodium chloride are obtained by treatment of the brine solution with barium carbonate instead of sodium carbonate, for this removes sulphates as well as calcium and magnesium. (Sodium Chloride B.P. must pass a limit test for barium.)

$$BaCO_3 + MgSO_4 = BaSO_4 + MgCO_3$$

After removal of impurities, the brine solutions are crystallized either by boiling or by vacuum evaporation.

*Metallic Sodium* is manufactured by the electrolysis of molten sodium hydroxide. The hydroxide is obtained from the chloride as described below. The direct manufacture by electrolysis of the molten chloride is uneconomic by virtue of the high temperature necessary to keep the mass molten.

Sodium is a soft white metal, with a bright lustre. It soon tarnishes on exposure to air. Sodium is very reactive, and displaces hydrogen readily from water, alcohol, and ammonia. It combines readily with the halogens, and many other nonmetals. Its oxide reacts readily with water and forms the strongly basic sodium hydroxide.

$$2Na + 2H_2O = 2NaOH + H_2$$

$$2Na + 2C_2H_5OH = \underset{\text{Sodium ethoxide}}{2C_2H_5ONa} + H_2$$

$$2Na + 2NH_3 = \underset{\text{Sodamide}}{2NH_2Na} + H_2$$

$$2Na + Cl_2 = 2NaCl$$

### Sodium Hydroxide

Sodium hydroxide is manufactured by the electrolysis of sodium chloride solutions. The primary products of the electrolysis are sodium (which forms sodium hydroxide by interaction with water) at the cathode, and chlorine at the anode. If the chlorine and sodium hydroxide are allowed to mix together, they react to form hypochlorites or chlorates (pp. 158, 160). For the manufacture of sodium hydroxide it is necessary to keep the cathodic and anodic products apart, and many different types of electrolytic cell have been designed for this purpose.

In the *Castner-Kellner* cell, mercury is used as the cathode to dissolve the sodium formed by the electrolysis. The sodium amalgam is circulated to another more isolated part of the cell, where the sodium reacts with water to form sodium hydroxide. In other cells the alkaline cathodic liquid is kept apart from the anodic liquid by porous partitions or diaphragms.

Sodium hydroxide is manufactured from sodium carbonate solution by boiling it with lime. Calcium carbonate is precipitated.

$$Na_2CO_3 + Ca(OH)_2 = 2NaOH + CaCO_3$$

Sodium hydroxide usually contains carbonate derived by reaction with the carbon dioxide of the air. It may be freed from carbonate by taking advantage of the fact that sodium carbonate is insoluble in alcohol, while the hydroxide is soluble. The official assay process for Sodium Hydroxide involves determinations of both carbonate and hydroxide. The titration is carried out after adding barium chloride and using phenolphthalein as indicator. It is subsequently continued using bromophenol blue as indicator. The first part corresponds to the reaction of the acid with the hydroxide alone, since the carbonate is converted to barium carbonate, which is insoluble in acid until the indicator change point of phenolphthalein has been passed. The second part therefore gives the extra amount of acid required to react on the carbonate. The official results are expressed in terms of sodium carbonate ($Na_2CO_3$) and total alkali, calculated as NaOH.

$$Na_2CO_3 + BaCl_2 = BaCO_3 + 2NaCl$$

Sodium hydroxide is a deliquescent highly caustic solid.

It dissolves in water to form a strongly alkaline solution, which neutralizes acids forming salts. Sodium hydroxide is a strong base. Its salts with strong acids are neutral in solution, and its salts with weak acids (sodium carbonate, sodium borate, sodium cyanide) are alkaline in reaction. By reason of its strong alkalinity, sodium hydroxide reacts with glass, so that alumina and silica derived from glass containers may be present as impurities.

*Soda Lime* is a solid absorbent for carbon dioxide obtained by slaking quicklime with sodium hydroxide solution. It is freed from water by heating until fusion takes place.

The oxide ($Na_2O$) corresponding to sodium hydroxide can be prepared, but when sodium is heated in air, *sodium peroxide* ($Na_2O_2$) is obtained. This is a powerful oxidizing agent related to hydrogen peroxide, which may be prepared by reacting on it with an acid.

## The Salts of Sodium

These are often important for their acid radical content, and for this reason they are mostly described under the corresponding acid.

Sodium salts usually crystallize with water of crystallization. Many of the hydrated crystals are efflorescent, and the anhydrous salts are sometimes hygroscopic. For this reason, the more expensive potassium compounds are often preferred, as they crystallize without water of crystallization.

Sodium salts can be prepared (1) from sodium chloride by displacement of the hydrochloric acid by a less volatile acid such as sulphuric acid, (2) by neutralization of the acid with sodium hydroxide, or (3) by neutralization of the acid with sodium carbonate.

*Sodium Carbonate* is prepared by heating sodium bicarbonate. (During this heating, any ammonium compounds present as impurities in the bicarbonate are driven off, so that no test for ammonium compounds is necessary in Sodium Carbonate B.P.)

$$2NaHCO_3 = Na_2CO_3 + CO_2 + H_2O$$

Anhydrous and hydrated sodium carbonate ($Na_2CO_3$, $10H_2O$) are official in the *British Pharmacopœia*.

Anhydrous sodium carbonate is a white powder, soluble in water forming an alkaline solution. The solution deposits crystals of various hydrates, the decahydrate ($Na_2CO_3$, $10H_2O$, washing-soda) being the most important. This hydrate loses water on exposure to air and becomes coated with a white powder of the monohydrate, ($Na_2CO_3 \cdot H_2O$).

*Sodium Bicarbonate* is manufactured by the ammonia-soda or *Solvay* process, which depends on the slight solubility of sodium bicarbonate in water. When sodium chloride and ammonium bicarbonate solutions are mixed, double decomposition occurs, and sodium bicarbonate is precipitated.

$$NaCl + NH_4HCO_3 = NaHCO_3 + NH_4Cl$$

In the manufacturing process, brine is saturated with ammonia, and the solution is dropped down a tower up which a current of carbon dioxide is being passed. The carbon dioxide and ammonia combine to form ammonium bicarbonate which reacts with the brine, precipitating sodium bicarbonate.

$$NH_3 + CO_2 + NaCl + H_2O = NaHCO_3 + NH_4Cl$$

The sodium bicarbonate falls as a pasty mass to the bottom of the tower, where it is filtered off and dried.

The efficiency of this process depends firstly on the fact that the brine can be used directly as pumped from the salt mine, thus avoiding the costly evaporation and crystallization of the salt; and secondly on the efficiency of the recovery of the ammonia. The carbon dioxide is obtained by the burning of limestone with coke; the lime formed is used to recover the ammonia from the ammonium chloride formed in the main reaction, so that, apart from incidental losses, limestone, coke, and brine are the only raw materials necessary.

$$CaCO_3 = CaO + CO_2$$

$$CO_2 + NH_3 + H_2O + NaCl = NaHCO_3 + NH_4Cl$$

$$CaO + 2NH_4Cl = CaCl_2 + 2NH_3 + H_2O$$

Sodium bicarbonate is a white powder, slightly soluble in water, forming a solution which is neutral to phenolphthalein. The presence of carbonate as impurity renders the solution more alkaline, and the *p*H reaction of the solution is used officially to control the presence of excessive quantities of carbonate. The sodium carbonate present in Compound Tablets of Sodium Bicarbonate is assayed by titration with an indicator neutral to the bicarbonate.

$$Na_2CO_3 + HCl = NaCl + NaHCO_3$$

Sodium Bicarbonate and Sodium Carbonate are officially assayed by direct titration with acid using an indicator such as methyl orange which is not affected by carbon dioxide.

$$2NaHCO_3 + H_2SO_4 = Na_2SO_4 + 2CO_2 + 2H_2O$$
$$Na_2CO_3 + H_2SO_4 = Na_2SO_4 + CO_2 + H_2O$$

## Determination of Sodium Compounds

As sodium salts are soluble, sodium compounds are not conveniently determined on their metal content. They are assayed on their acid radical content.

When an organic compound containing sodium is ignited, the metal remains as the carbonate. Certain organic sodium salts are assayed by ignition to carbonate followed by titration with acid (cf. p. 418).

## POTASSIUM

In igneous rocks, potassium and sodium are present to an approximately equal extent, but while the sodium salts are washed out and transferred to the sea, the potassium salts remain on land in clays, etc. Consequently, although potassium salts have a wide distribution, they are only found in commercially workable quantities in a few scattered localities.

The chief sources of potassium salts are the deposits found at Stassfurt and in Alsace. These deposits have been formed by gradual evaporation of water from inland seas, when the dissolved salts present in the sea water were deposited in the inverse order of their solubility. At Stassfurt, the lowest zone found (which represents the least soluble salt) contains calcium sulphate (as gypsum $CaSO_4, 2H_2O$; and anhydrite $CaSO_4$). Above this lie in order zones containing sodium chloride; polyhalite ($2CaSO_4, K_2SO_4, MgSO_4, 2H_2O$); kieserite ($MgSO_4, 2H_2O$); and carnallite ($KCl, MgCl, 6H_2O$). The top layer is covered with a thick clay which has prevented the underlying salt deposits being dissolved away. The zones contain other salts of calcium, magnesium, and potassium in addition to the more typical minerals named.

Potassium salts are extracted from carnallite by dissolving it in hot water or in the mother liquor from previous extractions. On cooling, potassium chloride crystallizes out leaving the more soluble magnesium chloride in solution. The first crystals contain sodium and magnesium chlorides, and smaller proportions of bromides, etc. After filtration and washing, they are redissolved and purified by recrystallization.

A certain amount of potassium compounds is also obtained from the residue of potassium carbonate which remains when various waste vegetable products are ignited. (Potassium is an essential constituent of plants.)

*Potassium* is a white metal, whose properties resemble those of sodium. It enters into corresponding chemical reactions, but with considerably greater vigour. It is prepared by electrolysis of fused potassium hydroxide.

## Potassium Hydroxide

Potassium hydroxide is prepared from potassium chloride by electrolysis, in the same way as sodium hydroxide is prepared from sodium chloride. The properties of potassium hydroxide are similar to those of sodium hydroxide, and the official assay process is also similar.

## The Salts of Potassium

Potassium salts are generally more easily crystallized and purified than the corresponding sodium salts. They crystallize normally without water of crystallization. They resemble the sodium salts in their chemical reactions.

The capacity of potassium iodide to react with iodine to form a tri-iodide ($KI_3$) forms a link with rubidium and caesium which form even more complex compounds (e.g. $CsI_5$).

*Potassium Carbonate* is obtained by ignition of vegetable waste products such as beet-sugar mother-liquors. The potassium present remains as the carbonate. Potassium carbonate is also prepared from the deposits at Stassfurt, by passing carbon dioxide into potassium chloride solution in presence of magnesium carbonate. A double salt ($KHCO_3$, $MgCO_3$, $4H_2O$) is precipitated, which is converted into potassium carbonate by the addition of magnesia. In this process, all the magnesium is recovered in a state suitable for using again.

$$2KCl + CO_2 + 3MgCO_3 + 9H_2O$$
$$= MgCl_2 + 2(MgCO_3, KHCO_3, 4H_2O)$$

$$2(KHCO_3, MgCO_3, 4H_2O) + MgO$$
$$= K_2CO_3 + 3MgCO_3 + 9H_2O$$

Potassium carbonate may also be obtained by heating a mixture of potassium sulphate, lime, and coal (*Leblanc* process). The potassium carbonate is dissolved from the residue in water.

$$K_2SO_4 + CaCO_3 + 4C = K_2CO_3 + CaS + 4CO$$

It can also be prepared by the interaction of carbon dioxide and potassium hydroxide.

*Potassium Bicarbonate* is prepared from the carbonate by reaction with carbon dioxide in solution. It cannot be prepared by the process corresponding to the ammonia-soda process for sodium bicarbonate, owing to its greater solubility in water.

$$K_2CO_3 + CO_2 + H_2O \quad 2KHCO_3$$

Other potassium salts are discussed under their acid radical.

## Determination of Potassium

Potassium salts may be determined gravimetrically by taking advantage of the fact that potassium perchlorate is insoluble in alcohol. It is often more convenient (as in the case of the official salts) to assay them on their acid radical content.

# CHAPTER XV

# THE ALKALINE EARTH METALS

THE five elements beryllium, magnesium, calcium, strontium and barium are chemically related. They are metals forming only bivalent compounds. They have characteristic flame colours. The elements are reactive, and combine with most non-metals. With the exception of beryllium, they displace hydrogen from water or steam, forming hydroxides which are strong bases. Not all their salts are soluble in water. The alkalinity and the infusibility of their oxides gave rise to the general name: alkaline earth metals. Beryllium differs from the other elements in many ways and shows a general resemblance to aluminium.

## MAGNESIUM

Magnesium is a plentiful constituent of igneous rocks, where it occurs as silicates. It is dissolved from these rocks as the bicarbonate, and precipitated as carbonate, often with calcium carbonate (e.g. dolomite $CaCO_3$, $MgCO_3$). Magnesium salts are present in many natural waters and in sea water. The Stassfurt and similar deposits were the chief source of magnesium compounds, but considerable quantities are now obtained from sea water by a process which involves precipitating magnesium hydroxide by milk of lime.

$$MgSO_4 + Ca(OH)_2 = Mg(OH)_2 + CaSO_4$$

*Magnesium Metal* is prepared by electrolysis of fused carnallite. It is a light metal, which can be drawn into wire and rolled to ribbon. It forms an important constituent of most light alloys, and it is also used in the manufacture of flash-powders and star shells, by reason of the bright light emitted when it burns in air.

Magnesium is a reactive element. It burns readily in air, forming a mixture of oxide and nitride.

$$2Mg + O_2 = 2MgO$$

$$3Mg + N_2 = Mg_3N_2$$

It decomposes boiling water, and is dissolved readily by acids.

$$Mg + H_2O = MgO + H_2$$
$$Mg + 2HCl = MgCl_2 + H_2$$

The salts of magnesium differ in some respects from those of calcium, strontium and barium, and resemble the corresponding salts of zinc (e.g. $MgSO_4$, $7H_2O$ and $ZnSO_4$. $7H_2O$ are isomorphous).

## Magnesium Oxide

Magnesium oxide may be obtained either by burning the metal in air or by the action of heat on the carbonate.

$$MgCO_3 = MgO + CO_2$$

It is used as a refractory for lining furnaces, for which purpose it is prepared from the naturally occurring carbonate, magnesite.

*Light and Heavy Magnesium Oxides* are prepared by heating the corresponding Light or Heavy Magnesium Carbonates.

Magnesium oxide is slightly soluble in water, forming an alkaline solution which contains the hydroxide [$Mg(OH)_2$].

*Mixture of Magnesium Hydroxide* is a suspension of the oxide (freshly prepared) in water. It is assayed on its alkalinity by adding excess standard sulphuric acid, followed by back titration.

$$Mg(OH)_2 + H_2SO_4 = MgSO_4 + 2H_2O$$

## Magnesium Salts

*Magnesium Carbonate* occurs naturally as magnesite. It may be prepared by precipitation, but under ordinary conditions, the addition of sodium carbonate produces precipitates of basic carbonates of varying composition. Light Magnesium Carbonate B.P. is prepared by boiling together dilute solutions of sodium carbonate and magnesium sulphate. The heavy variety is obtained by mixing boiling concentrated solutions, and after evaporation to dryness, washing the residue to remove soluble salts.

It is probable that the first reaction of sodium carbonate and magnesium sulphate results in the formation of a double sodium magnesium carbonate, which is subsequently hydrolyzed with loss of carbon dioxide.

$$MgSO_4 + Na_2CO_3 = MgCO_3 + Na_2SO_4$$
$$MgCO_3 + Na_2CO_3 = Mg(CO_3Na)_2$$
$$Mg(CO_3Na)_2 + H_2O = Mg(HCO_3)(OH) + Na_2CO_3$$
$$Mg(HCO_3)(OH) = Mg(OH)_2 + CO_2$$

The light and heavy varieties of magnesium carbonate have approximately the same composition (approximately $3MgCO_3, Mg(OH)_2, 4H_2O$). But owing to the different conditions of preparation, impurities are present in different proportions. The heavy variety contains a greater proportion of soluble salts which are hard to remove by washing from the evaporated residue, while the lighter variety contains more calcium as a larger quantity of water is used during its preparation. (The quantity of calcium present is officially determined gravimetrically, taking advantage of the insolubility of calcium sulphate in alcoholic dilute sulphuric acid in which magnesium sulphate is soluble.)

Magnesium carbonate is insoluble in water, but dissolves readily as magnesium bicarbonate in water containing carbon dioxide.

$$MgCO_3 + CO_2 + H_2O = Mg(HCO_3)_2$$

The presence of dissolved magnesium bicarbonate in water leads to temporary hardness (p. 256).

The official Solution of Magnesium Bicarbonate is prepared from freshly precipitated carbonate by dissolving in water in an atmosphere of carbon dioxide under 3 atmospheres pressure.

$$MgSO_4 + Na_2CO_3 = MgCO_3 + Na_2SO_4$$
$$MgCO_3 + CO_2 + H_2O = Mg(HCO_3)_2$$

If the precipitated magnesium carbonate has not been sufficiently washed, the final product will contain sodium bicarbonate. The amount present is controlled by a limit of alkali. The solution is evaporated to dryness, the residue is ignited to convert the magnesium carbonate to oxide. The soluble alkali is then dissolved from the magnesium oxide in water, and after filtration the solution is titrated with standard acid.

Solution of Magnesium Bicarbonate B.P. is assayed by direct titration with standard acid. The proportional amount of acid which reacts on the soluble alkali present should be subtracted from the titration value.

$$Mg(HCO_3)_2 + H_2SO_4 = MgSO_4 + 2H_2O + 2CO_2$$

*Magnesium Sulphate* is present in many natural waters to which it confers permanent hardness (p. 236). It is obtained by recrystallization of the mineral kieserite ($MgSO_4$. $H_2O$) which occurs in the Stassfurt deposits, or by dissolving magnesium carbonate in sulphuric acid. (Dolomite may be used, in which case the insoluble calcium sulphate is removed by filtration.)

Magnesium sulphate crystallizes from water with seven molecules of water of crystallization. The official test for limit of iron depends on the formation of basic iron sulphate when a solution of Magnesium Sulphate containing iron is heated.

*Magnesium Trisilicate* is prepared by double decomposition from magnesium sulphate and sodium silicate solution. It is not representable by a simple formula, containing excess silicic acid compared with magnesium orthosilicate $Mg_2SiO_4$. Its approximate composition is given as $2MgO, 3SiO_2$ with a variable amount of water.

MAGNESIUM CHLORIDE crystallizes from water with six molecules of water of crystallization. It cannot be rendered anhydrous by evaporation, as a basic salt is formed. The anhydrous salt can be obtained by heating the double magnesium ammonium chloride ($MgCl_2$, $NH_4Cl$, $6H_2O$) which loses first water, and then ammonium chloride.

## Determination of Magnesium

Assay $MgSO_4$

The determination of magnesium (as in the official assay of Magnesium Sulphate and Trisilicate) is based on the precipitation of magnesium ammonium phosphate by the addition of sodium phosphate to an ammoniacal solution of a magnesium salt. After filtration, the precipitate is ignited and converted into, and weighed as magnesium pyrophosphate.

$$\begin{aligned} Na_2HPO_4 + NH_4OH + MgSO_4 \\ = Na_2SO_4 + NH_4MgPO_4 + H_2O \end{aligned}$$

$$2NH_4MgPO_4 = 2NH_3 + H_2O + Mg_2P_2O_7$$

## CALCIUM

Calcium is a widely occurring element. In igneous rocks it occurs as silicates and alumino-silicates. It is dissolved as the bicarbonate, and reprecipitated by loss of carbon dioxide or through organic agencies as calcium carbonate. The large deposits of chalk and limestone are the chief sources of calcium compounds. Calcium occurs in animal and vegetable matter, e.g. bones consist mainly of calcium phosphate.

*Calcium Metal*, which can be obtained by electrolysis of fused calcium chloride, is a lustrous metal, which tarnishes rapidly in air. It is reactive, and combines with most non-metals. It displaces hydrogen from water.

### Calcium Oxide

Quicklime is obtained by the action of heat on the natural forms of calcium carbonate. Many lime kilns are designed for continuous operation, limestone and fuel being added at the top of the kiln, while lime is withdrawn at the bottom. A purer product is obtained in a discontinuous type of kiln, which is built up for each firing. Lime obtained by these processes contains all the non-volatile impurities in the original limestone and fuel (e.g. magnesia, alumina, silica, and iron oxides), and to obtain the purest products, special care has to be taken in the choice of the raw material.

$$CaCO_3 = CaO + CO_2$$

Calcium oxide is a white infusible solid. It is very caustic. It reacts vigorously with water to form calcium hydroxide (slaked lime).

*Calcium Hydroxide* is a strong base, slightly soluble in water giving an alkaline solution.

*Calcium Hydroxide B.P.* is assayed by direct titration, after separation from the calcium carbonate which may be present. The separation depends on the solubility of the hydroxide in a solution of sucrose, in which the carbonate is not soluble. (Sucrose forms soluble compounds with the hydroxides of calcium, strontium and barium.) The sample is moistened with neutralized alcohol to prevent caking, and then shaken for four hours with a 10 per cent sucrose solution. An aliquot part of the solution is filtered, and the filtrate titrated with N. hydrochloric acid. (Sulphuric acid would precipitate calcium sulphate from the concentrated solutions used.)

*Solution of Lime* is assayed officially by direct titration with N/10 sulphuric acid using phenolphthalein as indicator.

In addition to its medicinal uses, lime is used as a refractory for furnace linings, as a caustic for the removal of hair from hides, to purify coal-gas, as a fertilizer, and as an essential constituent of mortar, cement, glass and bleaching-powder (p. 159).

*Calcium Carbide* is prepared by heating together lime and coke in an electric furnace.

$$CaO + 3C = CaC_2 + CO$$

It is decomposed by water forming acetylene, from which many organic substances are prepared (p. 334).

$$CaC_2 + 2H_2O = Ca(OH)_2 + C_2H_2$$

Calcium carbide combines with nitrogen to form calcium cyanamide, from which ammonia is obtained by hydrolysis. Calcium carbide is used in one process for the fixation of atmospheric nitrogen.

$$CaC_2 + N_2 = \underset{\text{Calcium cyanamide}}{CaCN_2} + C$$

$$CaCN_2 + 3H_2O = CaCO_3 + 2NH_3$$

## The Salts of Calcium

*Calcium Carbonate* is the most important source of calcium. Most deposits are of organic origin, being formed from the skeletons and shells of marine organisms. Marble is formed by the melting and subsequent crystallization of such deposits under pressure. Calcium carbonate deposits are formed in caves in limestone regions owing to the escape of carbon dioxide from water containing dissolved calcium bicarbonate. Calcium carbonate is found in nature in two crystalline forms, calcite being the more stable, and aragonite the less stable form.

There are two official forms of calcium carbonate, the precipitated form and natural chalk. The precipitated form is prepared by the reaction of a soluble calcium salt with a soluble carbonate. The precipitate is filtered, washed, and dried.

$$CaCl_2 + Na_2CO_3 = CaCO_3 + 2NaCl$$

The product may contain soluble alkali, if insufficiently washed.

In the official limit test for soluble alkali the sample is boiled with water to dissolve the sodium carbonate, the calcium carbonate is removed by filtration, and the filtrate is titrated with standard acid. In other respects, the impurity limits for natural chalk are less strict than for precipitated calcium carbonate. Both official forms are assayed by back titration acid-alkali methods.

Calcium carbonate is insoluble in water, but dissolves readily in presence of carbon dioxide as the bicarbonate. The solution of bicarbonate loses carbon dioxide readily, the carbonate being reprecipitated. Water which contains calcium or magnesium salts in solution is *hard* and will not form a lather with soap, owing to the precipitation of an insoluble salt of the fatty acid of the soap.

$$2(C_{15}H_{31} . COONa) + CaCl_2 = (C_{15}H_{31} . COO)_2Ca + 2NaCl$$

Water containing calcium or magnesium bicarbonate is *temporarily hard*, as boiling softens the water by precipitation of the carbonate.

$$Ca(HCO_3)_2 = CaCO_3 + CO_2 + H_2O$$

Water containing chloride or sulphate of these metals cannot be softened by boiling and is *permanently hard.*

The hardness of water can be determined by titration with a standard soap solution until a permanent lather is obtained. Water is softened either by addition of lime-water (for temporary hardness) or of sodium carbonate (for permanent hardness).

$$Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3 + 2H_2O$$
$$CaSO_4 + Na_2CO_3 = CaCO_3 + Na_2SO_4$$

Other processes for water softening include the base-exchange process, whereby calcium is absorbed by reaction with a zeolite mineral (sodium aluminosilicate). The absorption is reversible and the zeolite can be regenerated for further use by soaking in a strong solution of brine.

$$2NaX + CaCl_2 \rightleftharpoons CaX_2 + 2NaCl$$

where X represents the aluminosilicate complex of the zeolite. Sodium hexametaphosphate is also used for softening water.

*Calcium Fluoride* ($CaF_2$) occurs in igneous veins as fluorspar.

*Calcium Chloride* is obtained as a by-product from the manufacture of sodium carbonate. A purer product is obtained by dissolving calcium carbonate in hydrochloric acid. It crystallizes with six molecules of water of crystallization. On heating the crystals, the water can be driven off without appreciable hydrolysis, but prolonged heating may cause a slight loss of hydrochloric acid.

$$CaCl_2 + H_2O = CaO + 2HCl$$

The anhydrous salt is a powerful drying agent and is deliquescent.

*Calcium Chloride B.P.* should dissolve to give a clear solution, but if free alkali is present a turbid solution is formed. The free alkali is officially limited by the amount of acid required to neutralize the solution to bromothymol blue.

*Calcium Sulphate* occurs naturally as gypsum ($CaSO_4$, $2H_2O$) and anhydrite ($CaSO_4$). It is not very soluble in water, and may be precipitated from concentrated solutions.

Gypsum is used in the manufacture of plaster of Paris ($2CaSO_4$, $H_2O$) which is obtained by its partial dehydration

$$2CaSO_4, 2H_2O \quad 2CaSO_4, H_2O + 3H_2O$$

## Determination of Calcium

Calcium can be precipitated quantitatively as the oxalate from neutral or ammoniacal solution. After filtration, the oxalate can be determined volumetrically. It is dissolved in sulphuric acid and the liberated oxalic acid is titrated with standard potassium permanganate solution. This is the basis of the official assays of the calcium salts.

$$CaC_2O_4 + H_2SO_4 = CaSO_4 + H_2C_2O_4$$

For the gravimetric determination, the oxalate is converted into carbonate or oxide by ignition.

The official method for the assay of calcium in Compound Syrup of Ferrous Phosphate depends on the conversion of the calcium oxalate into calcium sulphate. The iron is kept in solution by the presence of ammonium citrate during the precipitation of the oxalate. After the oxalate has been ignited, sulphuric acid is added and the mass is re-ignited. The calcium is then weighed as sulphate.

$$CaC_2O_4 = CaCO_3 + CO$$

$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$

## STRONTIUM AND BARIUM

Strontium and barium are not found abundantly in the earth's crust. The chief sources of their compounds are the sulphates ($SrSO_4$ and $BaSO_4$), which occur in igneous veins with the sulphides of other metals. When the sulphates are heated with carbon they are reduced to sulphides. The other salts of these metals can be obtained from the sulphides by reaction with an acid, or by double decomposition reactions.

$$BaSO_4 + 4C = BaS + 4CO$$

$$BaS + 2HCl = BaCl_2 + H_2S$$

$$BaS + CaCl_2 = BaCl_2 + CaS$$

$$BaS + Na_2SO_4 = BaSO_4 + Na_2S$$

*Strontium and Barium Hydroxides* are soluble in water, forming strongly alkaline solutions. The corresponding oxides react with oxygen to form peroxides.

*Barium Peroxide* is used in the manufacture of hydrogen peroxide.

$$2BaO + O_2 = 2BaO_2$$

$$BaO_2 + H_2SO_4 = BaSO_4 + H_2O_2$$

*Barium Sulphate* is very insoluble [cf. its use in the gravimetric determination of sulphate (p. 116)]. The official identity test depends on the application of the solubility product principle (p. 55).

As large doses may be administered prior to X-ray examinations, precipitated *Barium Sulphate B.P.* must contain no perceptible traces of soluble barium salts, or other dangerous impurities. The official tests are carried out as follows—

*Limit of metallic impurities:* 10 g of the sample are boiled with 30 mils of acetic acid and 70 mils of water, and filtered. Soluble barium salts and all other acid-soluble impurities are contained in the filtrate, which also contains a small quantity of dissolved barium sulphate. Half the solution, after evaporation to dryness, should leave a residue weighing not greater than 0·025 g. This residue is digested with water (any barium sulphate dissolved by the acetic acid now remains undissolved and is removed by filtration). The soluble barium salts are detected by the addition of sulphuric acid (which should form no turbidity or precipitate of barium sulphate within one hour). The other metallic impurities are detected by precipitation as sulphides with hydrogen sulphide using another portion of the filtrate from the acetic acid digestion. The darkening produced is compared with a standard.

*The test for phosphate* depends on the reaction with ammonium molybdate in the presence of nitric acid.

*Sulphides, sulphites, and thiosulphates*, if present, would be detected by an undue blackening of the lead acetate paper in the arsenic test.

## CHAPTER XVI

## THE EARTH METALS

**The** oxides of the tervalent metallic elements which include aluminium are known as the *earths*, and the metals are known as the *earth metals*. Boron (p. 238) is included with these elements in the third group of the Periodic Table. It differs from its companions in many ways, and shows a distinct resemblance to silicon.

### ALUMINIUM

Aluminium is the most widely occurring metal. It forms about 8 per cent of the earth's crust, mainly in the form of aluminates, aluminosilicates, and hydrated aluminium silicates.

Pure aluminium oxide crystals occur in nature as corundum, and, when coloured by other metallic oxides, as ruby, sapphire, and emery.

No process has yet been devised for the economic separation of aluminium from sources such as clay, which contain silica. The metal is obtained by electrolysis of bauxite (which is a hydrated aluminium oxide free from silica). Other metals are first removed by reactions in solution, and the purified bauxite is electrolyzed from a solution in molten cryolite ($Na_3AlF_6$). The reaction may be represented by the equation—

$$\underset{\text{Bauxite}}{2Al_2O_3} \qquad 4Al + 3O_2$$

Aluminium is a white lustrous metal (in time the lustre fades to a duller tone as the surface of the metal becomes coated with a thin film of oxide). Aluminium can be worked at temperatures above 200°C. It forms the basis of many alloys, which are not only light but possess great tensile strength. [Such alloys are magnalium (aluminium + 2–10 per cent magnesium) and duralumin.]

Aluminium is fairly resistant to chemical attack, owing to the ease with which a resistant oxide film is formed over its surface. Aluminium has a great affinity for oxygen, and displaces many other metals from their oxides. (Metals such as iron and chromium may be obtained from their oxides by reduction with aluminium as in the *thermit* process. The heat of reaction is sufficient to melt the metal obtained.)

Aluminium forms compounds with many non-metals, e.g. with chlorine ($AlCl_3$), nitrogen ($AlN$), and carbon ($Al_4C_3$). Aluminium carbide yields methane on decomposition with water (p. 326).

## Compounds of Aluminium.

*Aluminium Oxide* is a very refractory substance. It is resistant to chemical attack. The hydroxide is amphoteric, and dissolves readily in acids and in alkalis forming aluminium salts and aluminates respectively. Both classes of salts are easily hydrolyzed, the hydroxide being precipitated.

*Aluminium Chloride* cannot be obtained in the anhydrous form by direct evaporation of an aqueous solution, owing to hydrolysis. Anhydrous aluminium chloride is prepared by the reaction of chlorine or hydrogen chloride on aluminium.

### ALUMINIUM SULPHATE AND THE ALUMS

The most important salts of aluminium are the sulphate and the double sulphates, the alums. The alums are a group of isomorphous double sulphates of the general formula

$$M_2SO_4,\ M_2(SO_4)_3,\ 24H_2O$$

They crystallize in octahedra. A large number of alums have been obtained containing different univalent and tervalent metals.

Aluminium sulphate is obtained from china clay by the action of dilute sulphuric acid.

$$Al_2Si_2O_7,\ 2H_2O + 3H_2SO_4 = Al_2(SO_4)_3 + 2SiO_2 + 5H_2O$$

It is usually converted into its double salts with either ammonium or potassium sulphate. These alums are also made by roasting alum shale. Alum shale originally contained iron pyrites and clay. By oxidation during weathering, sulphuric acid and ferrous sulphate are formed from the pyrites, so that on heating aluminium sulphate is formed by reaction with the clay. The alums are obtained by adding potassium or ammonium sulphate to the solution of aluminium sulphate and crystallizing.

*Alum B.P.* may be either potassium or ammonium aluminium sulphate. Special tests are included in the *British Pharmacopœia* which limit the ammonium alum in potassium alum and the potassium alum in ammonium alum. The first depends on the Nessler reagent reaction (p. 190) and the second test is carried out after removing the aluminium by precipitation with ammonia, and igniting until the ammonium salts have been driven off. The residue (potassium sulphate) should weigh not more than 0·005 g from a 1 g sample.

## Determination of Aluminium

Aluminium is determined gravimetrically (as in the official assay of Alum) by precipitation with ammonia as aluminium hydroxide. On ignition, the hydroxide is converted to the oxide, which can be weighed.

### The Rare Earth Elements

The rare earth elements form a group of fifteen tervalent metals. The rare earth oxides occur together in nature, and their separation is very difficult owing to the close similarity in their chemical properties. Cerium, which is the most important of these elements, differs from the others in forming a series of quadrivalent compounds as well as tervalent compounds. Ceric salts are powerful oxidizing agents, and ceric sulphate is an important volumetric oxidizing reagent. This solution is conveniently prepared from ceric ammonium sulphate ($Ce(SO_4)_2$, $2(NH_4)_2SO_4$, $2H_2O$). On reduction the colour changes from yellow to colourless, but an internal indicator is often used to obtain a sensitive end-point.

$$2Ce(SO_4)_2 + H_2O = Ce_2(SO_4)_3 + H_2SO_4 + O$$

# CHAPTER XVII

# TIN AND LEAD

TIN and lead are the other important elements in the series of elements which includes carbon and silicon in the Periodic Table.

## TIN

The chief source of tin and its compounds is the mineral cassiterite or tinstone ($SnO_2$), which is found in igneous veins. The metal is obtained from this ore by reducing it by heating with anthracite.

$$SnO_2 + 2C = Sn + 2CO$$

(Tin is an expensive metal, and considerable quantities are therefore recovered from such materials as old tin-plate by treatment with chlorine forming stannic chloride.)

Tin is a soft lustrous metal, which is easily liquefied. It is an important constituent of various low melting alloys. In very cold weather the normal metallic form of tin may change slowly into grey tin (a crumbly amorphous powder). Grey tin is an allotropic form of ordinary tin and is stable below 18°C.

Tin is resistant to atmospheric corrosion and iron is therefore coated with tin to protect it (tin-plate).

Tin forms two sets of compounds with valencies two and four. The oxides ($SnO$ and $SnO_2$) are both amphoteric, so that tin forms bivalent stannous salts ($SnCl_2$) and stannites (derived from $H_2SnO_2$), and quadrivalent stannic salts ($SnCl_4$) and stannates (derived from $H_2SnO_3$).

*Stannous Chloride* is obtained by dissolving metallic tin in hydrochloric acid. It is a powerful reducing agent, and reduces ferric salts to ferrous salts, mercuric chloride to mercurous chloride and mercury, and arsenic compounds to arsenious compounds [cf. the official limit test for arsenic (p. 132)].

*Stannic Chloride* which is formed by the oxidation of stannous chloride, may be prepared by direct union of tin and chlorine. It is easily hydrolyzed, stannic hydroxide being precipitated.

*Stannous Sulphide* and *Stannic Sulphide* both dissolve in yellow ammonium sulphide solution to form ammonium thiostannate.

$$SnS + S + (NH_4)_2S = (NH_4)_2SnS_3$$
$$SnS_2 + (NH_4)_2S = (NH_4)_2SnS_3$$

On acidifying the solution obtained, stannic sulphide is precipitated.

### Determination of Tin

Tin can be determined by precipitation as sulphide, and conversion to (by ignition) and weighing as stannic oxide. Stannous salts may be determined by titration with an oxidizing agent.

## LEAD

The chief ore of lead is galena (lead sulphide, PbS), which occurs in mineral veins. The lead is obtained from this ore by heating it first in presence of air until the sulphide is partially oxidized, and then to a higher temperature in absence of air when the metal is obtained.

$$(1) \qquad PbS + 2O_2 = PbSO_4$$
$$2PbS + 3O_2 \quad 2PbO + 2SO_2$$
$$(2) \quad PbS + PbSO_4 = 2Pb + 2SO_2$$
$$2PbO + PbS = 3Pb + SO_2$$

The impure lead, which is very hard, is purified by removing other metals by heating in an oxidizing atmosphere (the impurities are oxidized before the lead). After this treatment the lead still contains bismuth and silver which are removed together. The high price of silver justifies the recovery, although only small quantities are present.

### Properties of Lead

Lead is a soft heavy metal which melts at a low temperature. Its softness enables it to be rolled into pipes and sheets. Most fusible alloys have a lead basis. (Lead and tin constitute solder; lead, tin, bismuth, and cadmium form fusible alloys which may melt at temperatures as low as 71°C.)

Lead is not a very reactive metal, and it is displaced from its salts by more reactive metals such as zinc. In absence of oxidizing agents, lead is not attacked by many of the common chemical reagents, but in presence of air it is attacked fairly rapidly by weak acids, e.g. acetic acid. Water containing carbon dioxide dissolves appreciable quantities of lead as the bicarbonate. Hard waters form a coating of insoluble carbonate or sulphate over the metal, and so do not attack it, and soft waters may have to be artificially hardened to prevent lead being dissolved from water-pipes.

## Compounds of Lead

Lead forms two series of compounds (bivalent and quadrivalent). Plumbous oxide ($PbO$) is chiefly basic. The corresponding hydroxide is alkaline in reaction and forms salts with acids. [It dissolves also in strong caustic alkalis forming plumbites (e.g. $K_2PbO_2$) but these compounds are unstable.] Plumbic oxide ($PbO_2$) is an amphoteric oxide, which forms the unstable plumbic salts ($PbCl_4$) and plumbates. Both orthoplumbates and metaplumbates are known, corresponding to the acids $H_4PbO_4$ and $H_2PbO_3$ respectively.

The other oxides of lead $Pb_3O_4$ (red lead) and $Pb_2O_3$ are often formulated as lead orthoplumbate $Pb_2(PbO_4)$ and lead metaplumbate $Pb(PbO_3)$ respectively. Red lead is obtained commercially by roasting litharge in air.

$$6PbO + O_2 \quad 2Pb_3O_4$$

*Lead Monoxide* (litharge) is obtained when the molten metal is oxidized in air. It can also be prepared by the action of heat on lead carbonate.

*Plumbous hydroxide* (which can be obtained by precipitation from a lead salt) is slightly soluble in water.

*Lead Chloride* can be obtained by reaction of lead monoxide with hydrochloric acid, or being sparingly soluble in cold water, by precipitation from a soluble lead salt and a chloride.

*Lead Nitrate* is obtained by the action of nitric acid on the metal, oxide or carbonate. On heating it decomposes into litharge, nitrogen dioxide and oxygen.

$$2Pb(NO_3)_2 = 2PbO + 4NO_2 + O_2$$

*Lead Acetate* is prepared by the action of acetic acid on litharge. It is slightly hydrolyzed in aqueous solution, and dissolves in water to give a milky solution which becomes clear on the addition of a little acetic acid.

The official test for metallic impurities in Lead Acetate is carried out (after the lead has been removed by precipitation as sulphate) by adding potassium ferrocyanide which forms insoluble ferrocyanides with iron, zinc, copper, etc.

Lead acetate solution dissolves appreciable quantities of lead monoxide. The resultant solution (*Solution of Lead Subacetate*) is strongly alkaline and contains a basic lead acetate [possibly $Pb(OH)_2$, $(CH_3.COO)_2Pb$].

*Lead Sulphide* is precipitated by the addition of hydrogen sulphide to a soluble lead salt. It is slightly soluble in acids, but almost insoluble in alkaline solution, so that small quantities of lead can be detected by precipitation in alkaline solution (cf. p. 128). Traces of certain sulphur compounds as impurities in Carbon Tetrachloride and Liquid Paraffin are officially detected by the formation of lead sulphide by reaction with a solution of lead hydroxide in potassium or sodium hydroxide solution (potassium or sodium plumbite). The removal of hydrogen sulphide from gases is achieved by its conversion to lead sulphide.

*Lead Carbonate.* The normal carbonate ($PbCO_3$) can be obtained by precipitation, but basic carbonates are more often obtained. A basic carbonate [$Pb(OH)_2$, $PbCO_3$] (white lead) is manufactured on a large scale by the action of acetic acid, air and carbon dioxide on metallic lead.

*Lead Dioxide* is obtained by treatment of red lead with nitric acid, when the monoxide is dissolved and the dioxide remains.

$$Pb_3O_4 + 4HNO_3 = 2Pb(NO_3)_2 + 2H_2O + PbO_2$$

Lead dioxide is a strong oxidizing agent, e.g. on heating it oxidizes bromides to bromine, and chlorides to chlorine. The corresponding quadrivalent lead salts ($PbCl_4$) are unstable and decompose readily.

$$PbO_2 + 4HCl = PbCl_4 + 2H_2O$$

$$PbCl_4 = PbCl_2 + Cl_2$$

## Determination of Lead

Lead may be determined gravimetrically as chromate. This is the basis of the official assays except for Solution of Lead Subacetate. For this substance the official method depends on the precipitation of insoluble lead oxalate by the addition of excess oxalic acid. The precipitate is filtered, and the excess oxalic acid is titrated with potassium permanganate.

$$(CH_3.COO)_2Pb + H_2C_2O_4 = PbC_2O_4 + 2CH_3.COOH$$
$$PbO + H_2C_2O_4 = PbC_2O_4 + H_2O$$

Solution of Lead Subacetate is also assayed for alkalinity. In this case the filtrate, after removal of lead oxalate, is titrated with standard sodium hydroxide. This enables the oxalic acid which has acted on the lead oxide to be calculated, since precipitation from lead acetate does not affect the acidity of the solution owing to the formation of an equivalent amount of acetic acid.

# CHAPTER XVIII

# THE TRANSITION ELEMENTS

## COPPER

**Copper** occurs in nature in the metallic state, but the important ores of copper consist of oxide, carbonate, or sulphide (mainly copper pyrites $CuFeS_2$). Different ores demand different treatments for the extraction of the metal. The oxides and carbonates can be reduced to the metal by heating with carbon, but the treatment of the sulphide ores is more complex for they contain iron sulphide which must be removed before the copper can be obtained by oxidizing away the sulphur.

$$CuO + C = Cu + CO$$

$$2CuS + 3O_2 = 2CuO + 2SO_2$$

$$Cu_2S + 2Cu_2O = 6Cu + SO_2$$

Crude copper contains about 2 per cent of impurities (the most important being arsenic, sulphur, and other metals). After a preliminary refining, the copper is purified by electrolysis, the final product being of a high degree of purity.

*Electrolytic Refining of Copper.* Copper sulphate solution is electrolyzed using an anode of crude copper and a cathode of pure copper. The copper is dissolved at the anode and deposited on the cathode. The gold and silver present in the copper remain as a sludge at the anode.

### Properties of Copper

Copper is a metal which possesses a characteristic colour and lustre. It is malleable and ductile, and possesses a high electrical and thermal conductivity (hence it is used for electric cables, and for boiler tubes, evaporating and heating pans). Copper forms with zinc the important series of alloys—the brasses; and alloys with tin (bronze) and nickel (german or nickel silver) are also important.

Metallic copper is not very reactive chemically. In dry air it retains its lustre indefinitely. It tarnishes rapidly in presence of hydrogen sulphide. It is not attacked by dilute acids, but strong oxidizing acids dissolve it. It combines when heated with the halogens, sulphur, and oxygen.

## Compounds of Copper

Copper forms two series of compounds, corresponding to the two basic oxides, cuprous oxide ($Cu_2O$), and cupric oxide ($CuO$).

The cuprous salts are generally white and insoluble in water and easily oxidized. The cupric salts are usually soluble in water, forming blue solutions. The cupric salts are the more important, and in these compounds copper shows a distinct resemblance to zinc. In the cuprous salts, copper resembles mercurous mercury.

Copper readily forms complex compounds, e.g. cuprous chloride absorbs carbon monoxide to form $Cu_2Cl_2 . CO, 2H_2O$ and $Cu_2Cl_2, 2CO, 4H_2O$; precipitated cupric hydroxide dissolves in ammonia to form the blue cuprammonium hydroxide $[Cu4NH_3] (OH)_2$: cupric cyanide dissolves in potassium cyanide solution to form the complex cyanide $[K_2Cu(CN)_4]$. This complex cyanide is sufficiently stable to prevent the precipitation of copper sulphide by hydrogen sulphide in presence of potassium cyanide (cf. the official lead limit test).

Potassium cupricyanide is colourless, and when potassium cyanide is added to a copper salt solution the blue colour disappears.

$$CuSO_4 + 4KCN - K_2SO_4 + K_2Cu(CN)_4$$

Copper is not precipitated by alkalis from a solution containing tartrates, due to the formation of complex compounds. (Fehling's solution is an alkaline potassium cupritartrate solution.)

*Cuprous Oxide* is obtained as a red powder by the reduction of an alkaline solution of a cupric salt (e.g. Fehling's solution).

*Cuprous Chloride* ($Cu_2Cl_2$) is prepared by boiling a strongly acid solution of cupric chloride with metallic copper. On pouring into water the cuprous chloride is precipitated as a white powder, which is readily oxidized on exposure to the air. Cuprous chloride solutions (acid or ammoniacal) readily absorb carbon monoxide and acetylene.

*Cuprous Bromide* and *Iodide* are more stable than cuprous chloride. Cupric iodide decomposes as soon as it is formed with the precipitation of cuprous iodide and liberation of iodine. This reaction is the basis of the volumetric method of determination of copper. Cuprous bromide, iodide, and cyanide are important reagents in organic chemistry (p. 504).

*Cupric Oxide* is obtained by heating copper, copper hydroxide, carbonate or nitrate in air. The hydroxide is precipitated from cupric salt solutions by sodium hydroxide.

*Copper Sulphate* is obtained by the action of dilute sulphuric acid on scrap copper in the presence of air, or from iron pyrites containing copper which has been burnt for the manufacture of sulphuric acid. The product from the latter source contains an appreciable quantity of ferrous sulphate which is not easily removed from copper sulphate. (The iron content is officially determined gravimetrically by precipitation with ammonia as ferric hydroxide, and ignition to ferric oxide.)

Copper sulphate crystallizes from water as blue crystals which contain five molecules of water of crystallization. On heating, a monohydrate is first obtained which is a paler blue, but when completely dehydrated the anhydrous salt is white. On addition of water, this substance becomes blue.

*Cupric Chloride* is obtained by direct action of chlorine on the metal, or as a hydrate, by neutralizing hydrochloric acid with copper oxide.

## Determination of Copper

Copper can be determined gravimetrically by conversion to cupric oxide, cupric sulphide, or cuprous thiocyanate, or by electrolytic deposition of the metal. The volumetric method adopted for the official assay of Copper Sulphate depends on the instability of cupric iodide. When potassium iodide is added to a weakly acid solution of a cupric salt, cuprous iodide is precipitated, and iodine is liberated. The iodine may be determined by titration with a standard solution of sodium thiosulphate.

$$2CuSO_4 + 4KI = 2CuI_2 + 2K_2SO_4$$

$$2CuI_2 = Cu_2I_2 + I_2$$

## SILVER

Silver is sometimes found in the metallic form, but the chief source is the silver sulphide ore, which occurs in metallic veins, mixed with other metallic sulphides. Silver is extracted from the ores by dissolving in potassium cyanide solution to form the complex cyanide $KAg(CN)_n$. The metal is reprecipitated by adding zinc. Considerable quantities of silver are separated in the refining of lead and copper. Silver can be purified electrolytically from a bath of the complex cyanide.

Silver is a metal whose white lustre persists in sulphur-free air. It has a high electrical and thermal conductivity. It is not very reactive chemically, and is insoluble in non-oxidizing acids. Silver forms compounds in which it is univalent. The oxide ($Ag_2O$) is a strong base, and dissolves in acids to form neutral salts. Silver-salts are generally not very soluble, and they crystallize easily without water of crystallization. Advantage is taken of the insolubilities of silver halides and silver thiocyanate in the gravimetric and volumetric determination of soluble halides.

Silver halides are decomposed by light, and they are used in the manufacture of sensitive photographic emulsions.

Silver salts are easily reduced to the metal. An ammoniacal silver nitrate solution is used as a sensitive reagent for the detection of reducing agents, e.g. aldehydes.

*Silver Nitrate* is prepared by dissolving the metal in dilute nitric acid. Silver nitrate is toughened by fusing it with 5 per cent of potassium nitrate.

## Determination of Silver

Silver may be determined gravimetrically by precipitation as chloride, or volumetrically by titration in nitric acid solution with standard ammonium thiocyanate solution using a soluble ferric salt as the indicator. The latter method is used for the official assay of Silver Nitrate and Toughened Silver Nitrate, and (after destroying organic matter by ignition) for Silver Protein.

$$AgNO_3 + NH_4CNS = AgCNS + NH_4NO_3$$

### Chemical Reactions Occurring during the Photographic Process

A coating of small granules of silver halide in gelatin is placed on glass or celluloid. After exposure to light, no visible effect is produced on this *emulsion* until the *latent image* is developed by the action of a reducing agent. After development, an image is obtained, whose density depends on the intensity of the light and time of exposure. The image is then fixed, by dissolving the unchanged silver halide in sodium thiosulphate solution.

$$AgBr + Na_2S_2O_3 = NaBr + NaAgS_2O_3$$

A negative is thus obtained, in which the light and dark portions of the original subject are reversed. By printing through the negative a positive reproduction is obtained.

While it is known that light decomposes silver halides into silver atoms and halogen atoms (which in their turn react with gelatin), the problem that development starts only at certain sensitive spots in a halide grain has to be explained. The explanation of this point is that the light acts by releasing electrons from the halide ions which are present together with silver ions in the crystal structure.

$$Br^- = Br + -$$

The electrons may combine with silver ions to form atoms or may recombine with bromine atoms to form ions, but most of them move to the sensitive spots on the surface of the plates (usually these are specks of silver sulphide formed from traces of sulphur compounds in the gelatin). The accumulation of electric charges at the sensitive spots initiates local electrolysis with the formation at these spots of metallic silver in sufficient amounts to initiate developer action. An exposed undeveloped plate contains scattered over its surface grains containing various aggregates of silver atoms, in abundance proportional to the light intensities at different parts of the surface.

It seems that a reducing agent does not reduce silver halides rapidly unless a small amount of metallic silver is present to act as a nucleus around which reduction can commence (cf. a supersaturated solution which only crystallizes when nuclei are present to act as centres of crystallization). Development consists in reducing the silver halide to silver around each of the silver nuclei formed by exposure to the light. This reduction may proceed until the whole silver halide grain is reduced, so that grain size affects the sensitivity of the emulsion. This latter quality also depends on the concentration of sensitive spots.

The ordinary photographic plate is most sensitive to blue light, but by adding to the emulsion certain dyes (which absorb light of different colours and pass the absorbed energy on to the silver halide) plates can be made sensitive to the yellow, red, and infra-red regions of the spectrum.

## GOLD

Gold is usually found native. It is extracted either by washing away the lighter rock fragments, or by dissolving it in potassium cyanide solution (in presence of air, gold reacts with potassium cyanide to form a soluble complex cyanide).

$$4Au + 8KCN + 2H_2O + O_2 = 4KOH + 4KAu(CN)_2$$

Gold can be recovered from the cyanide solution by electrolysis or precipitation with zinc. Crude gold contains silver, from which it is separated electrolytically or by taking advantage of the greater ease of attack of silver by acids.

Gold is a yellow metal, remarkably malleable and ductile. Gold leaf has been obtained a millionth of a centimetre thick. Gold leaf transmits light, the colour varying from green or blue to red according to the thickness. (The colour of colloidal gold solutions varies from blue to red, depending on the size of the gold particles which it contains.)

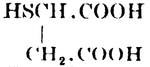
Gold is not a reactive element. It does not dissolve in single acids. Chlorine attacks gold, and the metal is dissolved by solutions containing free chlorine such as *aqua regia* (a mixture of nitric and hydrochloric acids). The compound obtained when gold is dissolved in this solvent is chloroauric acid ($HAuCl_4$), but this substance on heating can be converted into gold chloride ($AuCl_3$).

$$HNO_3 + 3HCl = NOCl + Cl_2 + 2H_2O$$

$$2Au + 3Cl_2 + 2HCl = 2HAuCl_4$$

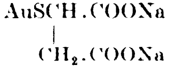
The compounds of gold are easily decomposed, and the metal is precipitated from its salts by the action of reducing agents. The metal is sometimes formed by reduction in so fine a state of division that it remains in colloidal suspension (colloidal gold).

Golds forms compounds corresponding to valencies one and three. With each class of compounds, a series of complex compounds are formed [e.g. potassium aurocyanide ($KAu(CN)_2$), and chloroauric acid.] The official organic gold compound (Sodium Aurothiomalate) is most simply represented as containing a hydrogen atom of thiomalic acid replaced by the univalent metal atom. This formula, however, does not agree with the tendency of gold to co-ordinate; the correct formula has yet to be established. The substance is assayed by destroying the organic matter and weighing the gold residue,



$$\begin{array}{l} HSCH.COOH \\ \quad | \\ \ CH_2.COOH \end{array}$$

Thiomalic acid



$$\begin{array}{l} AuSCH.COONa \\ \quad | \\ \ CH_2.COONa \end{array}$$

Sodium aurothiomalate

## ZINC, CADMIUM, AND MERCURY

Zinc, cadmium, and mercury are three volatile metals. They form compounds in which the metal is bivalent. Mercury also forms mercurous compounds in which the metal is possibly univalent. The compounds diminish in stability in the order zinc > cadmium > mercury.

Zinc and cadmium resemble one another closely, and always occur together in nature. Mercury differs from these two elements in several ways. Its compounds are very feebly ionized, and it forms many complex compounds (e.g. potassium mercuri-iodide, $K_2HgI_4$).

## ZINC

The chief ore of zinc is the vein mineral zinc blende (ZnS). This ore is converted into the oxide by roasting in air, and the metal is obtained by reduction of the oxide with coke or anthracite.

$$2ZnS + 3O_2 = 2ZnO + 2SO_2$$
$$2ZnO + 2C = 2Zn + 2CO$$

Crude zinc (or spelter) which distils from the furnace contains lead, cadmium, iron, arsenic, and carbon. The metal may be purified by oxidizing the lead and other impurities, followed by redistillation. Arsenic-free zinc can be prepared from crude zinc by heating it with metallic sodium, which removes the arsenic as sodium arsenate. Pure zinc is also obtained by electrolytic purification.

Zinc is a white metal, which is chemically reactive. It dissolves in dilute acids and alkalis evolving hydrogen. It is attacked by moist air containing carbon dioxide, a film of oxide or carbonate being formed. This attack of zinc proceeds preferentially to that of iron, and iron is therefore protected by coating it with a film of zinc (*galvanized iron*) by dipping clean sheet iron into molten zinc. Zinc is also used as an important constituent of alloys (e.g. brass is copper containing 20 per cent to 40 per cent of zinc).

### Zinc Oxide

The compounds of zinc are derived from zinc oxide ($ZnO$), which is obtained by oxidation of the metal by distilling it in a current of air. The fumes of zinc oxide are collected in condensing chambers. Zinc oxide is obtained when the corresponding hydroxide or carbonate is ignited. Zinc oxide is used as a pigment (zinc white).

For pharmaceutical purposes, the freedom of the product from unburnt metallic zinc is important. When Zinc Oxide is dissolved in dilute hydrochloric acid containing a little dissolved lead, the presence of metallic zinc would be revealed by the precipitation of metallic lead.

$$Zn + PbCl_2 = Pb + ZnCl_2$$

The hydroxide corresponding to zinc oxide can be obtained by precipitation. It is amphoteric, and behaves as a weak base and a weak acid. It dissolves in acids to form zinc salts, and in alkalis to form zincates.

$$Zn(OH)_2 + 2HCl = ZnCl_2 + 2H_2O$$
$$Zn(OH)_2 + 2KOH = K_2ZnO_2 + 2H_2O$$

Zinc hydroxide is soluble in ammonia, forming a complex hydroxide (possibly $3ZnO, 4NH_3, 12H_2O$). Ammonium salts therefore prevent the precipitation of zinc hydroxide by sodium hydroxide. Advantage is taken of this fact in the official *assay of Zinc Oxide.* It is assayed by the addition of excess standard acid and back titration with alkali in presence of ammonium chloride.

$$ZnO + H_2SO_4 = ZnSO_4 + H_2O$$

The presence of lead in Zinc Oxide cannot be detected by the ordinary lead limit test because zinc does not form a stable complex cyanide, and so zinc sulphide is precipitated (along with any lead sulphide) in ammoniacal solution by hydrogen sulphide in presence of potassium cyanide. The test for lead in Zinc Oxide is carried out by adding potassium chromate and acetic acid (lead chromate is insoluble in acetic acid).

$$(CH_3.COO)_2Pb + K_2CrO_4 = PbCrO_4 + 2CH_3.COOK$$

*Zinc Peroxide* is obtained by acting on zinc hydroxide with hydrogen peroxide. It is not a single substance and it has been variously pictured as being a hydrated zinc peroxide or a compound of zinc oxide and hydrogen peroxide. (Neither of these suggested compounds has yet been isolated in a pure state.) The official assay process is a titration with potassium permanganate as for hydrogen peroxide, the result being calculated as $ZnO_2$.

## The Salts of Zinc

Being a feeble base, zinc hydroxide forms salts which are easily hydrolyzed.

*Zinc Chloride.* Anhydrous zinc chloride cannot be obtained by evaporation of the aqueous solution obtained when the metal is dissolved in hydrochloric acid. On evaporation hydrolysis takes place and a basic salt is formed.

$$ZnCl_2 + H_2O = Zn(OH)Cl + HCl$$
$$ZnCl_2 + 2H_2O = Zn(OH)_2 + 2HCl$$

If the aqueous solution is gently evaporated under reduced pressure, the anhydrous salt can be obtained. It can also be prepared from the solution by adding ammonium chloride, after which the water can be removed without hydrolysis. A double salt is formed which loses water, leaving a residue of zinc chloride and ammonium chloride. The latter substance is driven off by stronger heating. Anhydrous zinc chloride can also be obtained by the reaction of chlorine on the metal, or on the zinc blende ore.

$$Zn + Cl_2 = ZnCl_2$$
$$ZnS + Cl_2 = ZnCl_2 + S$$

Zinc chloride is also used for preserving wood, for cleaning metals before soldering, and as a dehydrating agent.

*Zinc Sulphate* is prepared from the oxidized zinc blende ore, or by dissolving the metal in dilute sulphuric acid.

$$ZnS + 2O_2 = ZnSO_4$$
$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

It crystallizes with seven molecules of water of crystallization.

*Zinc Carbonate* is precipitated by soluble carbonates and bicarbonates from solutions containing zinc salts, but with excess water it gives a basic carbonate ($2ZnCO_3, 3Zn(OH)_2, H_2O$) which is the basis of the preparation, Calamine.

$$ZnSO_4 + Na_2CO_3 = ZnCO_3 + Na_2SO_4$$
$$ZnCO_3 + 2H_2O = Zn(OH)_2 + CO_2 + H_2O$$

*Zinc Stearate B.P.* is obtained by reacting with commercial sodium stearate on a zinc salt. Therefore it contains zinc palmitate.

Zinc Stearate is officially assayed on the total bases present (calculated as zinc oxide). The soap is decomposed with excess standard sulphuric acid. The fatty acids are removed by filtration, and the excess acid is determined by back titration with alkali.

$$Zn(St)_2 + H_2SO_4 = ZnSO_4 + 2HSt$$

Zinc Stearate should pass tests for limit of fatty acids (which are soluble in ether) and for limit of alkali and alkaline earth metals. (The fatty acids are removed by treatment with hydrochloric acid and filtration. The zinc is removed by precipitation as sulphide and filtration. The residual solution is evaporated to dryness and the residue is re-dissolved, re-evaporated and finally weighed.)

*Zinc Oleate* is prepared by reacting on zinc sulphate with hard soap (sodium oleate). It is assayed in the Ointment by an acid-alkali back titration method, the result being calculated as zinc oxide. The same assay method is adopted for the Zinc Oxide Ointments.

## Determination of Zinc

Zinc may be determined gravimetrically as the pyrophosphate (cf. magnesium), but a volumetric method is adopted for Zinc Sulphate. This depends on the precipitation of an insoluble zinc mercuric thiocyanate when ammonium mercuric thiocyanate is added to a solution of a zinc salt [ammonium mercuric thiocyanate $(NH_4)_2Hg(CNS)_4$ is a complex salt comparable with potassium mercuri-iodide $K_2HgI_4$ and is prepared in a corresponding way].

$$4NH_4CNS + HgCl_2 = (NH_4)_2Hg(CNS)_4 + 2NH_4Cl$$

$$ZnCl_2 + (NH_4)_2Hg(CNS)_4 = ZnHg(CNS)_4 + 2NH_4Cl$$

The zinc mercuric thiocyanate after filtration and washing is titrated with potassium iodate in hydrochloric acid solution. The thiocyanates are first oxidized by the iodate (which is reduced to the iodide), the sulphur being oxidized to sulphate.

$$\begin{aligned} &ZnHg(CNS)_4 + 4KIO_3 + 4H_2O \\ &\qquad = Zn(CN)_2 + Hg(CN)_2 + 4H_2SO_4 + 4KI \end{aligned}$$

The iodide formed during this stage then reacts with further quantities of the iodate solution in accordance with the equation

$$2KI + KIO_3 + 6HCl = 3ICl + 3KCl + 3H_2O$$

The final end-point is indicated by the disappearance of free iodine from the solution (a globule of chloroform is present to determine this point). The equation for the whole reaction is

$$\begin{aligned} &ZnHg(CNS)_4 + 6KIO_3 + 12HCl \\ &\qquad = ZnSO_4 + HgSO_4 + 4HCN + 6KCl + 6ICl \\ &\qquad\qquad + 2H_2SO_4 + 2H_2O \end{aligned}$$

i.e. $ZnSO_4 \equiv 6KIO_3$

## CADMIUM

Cadmium occurs in zinc ores and is obtained as a by-product of zinc smelting. It differs from zinc in being insoluble in alkali hydroxides. Its oxide and hydroxide are also insoluble. The salts are obtained from the metal by dissolving in acid or, in the case of the halides, by reaction with the halogens.

*Cadmium iodide* is used as a sensitive test for the presence of free chlorine.

## MERCURY

The chief source of mercury compounds is cinnabar (mercuric sulphide, $HgS$), which is found as a vein mineral. When this ore is roasted, crude mercury distils (for mercuric oxide is unstable and breaks down on heating).

$$HgS + O_2 = Hg + SO_2$$

Crude mercury contains other metals. It is purified by filtration through leather, and by redistillation. On a small scale mercury can be purified by distillation in vacuo or by treatment with dilute nitric acid which dissolves the more reactive metals.

*Mercury* is a heavy liquid metal, the freely running globules of pure mercury being very characteristic. It forms alloys (*amalgams*) with many metals; tin amalgam is used for coating mirrors, sodium amalgam is used as a reducing agent, and copper amalgam has been used in dentistry.

Mercury is not a very reactive metal. It is not soluble in dilute hydrochloric acid, but dissolves in oxidizing acids. Mercury forms two classes of compounds, mercurous compounds derived from the oxide $Hg_2O$, and mercuric compounds derived from the oxide $HgO$. Many of the mercurous compounds possess the double formula, in which mercury seems to be bivalent. For example, mercurous chloride crystals contain the molecule $Cl—Hg—Hg—Cl$, and very dry mercurous chloride vaporizes without decomposition to form molecules of the formula $Hg_2Cl_2$. (The half formula $HgCl$ is often used for simplicity of representation.)

### Mercurous Compounds

*Mercurous Oxide* is formed as a dark brown precipitate when sodium hydroxide is added to a solution of a mercurous salt.

*Mercurous Chloride.* The most important mercurous salt is mercurous chloride (calomel, $Hg_2Cl_2$). Mercurous chloride is precipitated as an insoluble white powder when a soluble mercurous salt is mixed with a solution of a chloride. It is prepared by heating mercuric chloride with mercury, or a mixture of mercuric sulphate and sodium chloride with mercury. The mercurous chloride sublimes. It may be freed from mercuric chloride by shaking with water.

$$HgCl_2 + Hg = Hg_2Cl_2$$
$$2NaCl + HgSO_4 + Hg = Na_2SO_4 + Hg_2Cl_2$$

Under ordinary conditions mercurous chloride, in common with most other mercurous compounds, decomposes on heating into the mercuric salt and mercury.

$$Hg_2Cl_2 = HgCl_2 + Hg$$

A similar conversion into a mixture of a mercuric compound and mercury takes place when ammonia is added to mercurous chloride. Mercuricammonium chloride and mercury are formed, the white mercurous chloride being blackened.

$$Hg_2Cl_2 + 2NH_3 = NH_2HgCl + Hg + NH_4Cl$$

*Mercurous Chloride B.P.* is assayed by oxidation with iodine in presence of potassium iodide. Excess standard iodine solution is added, and the excess iodine is titrated with sodium thiosulphate.

$$Hg_2Cl_2 + I_2 + 6KI = 2K_2HgI_4 + 2KCl$$

The presence of mercuric chloride is detected officially by shaking with cold water, filtering, and passing hydrogen sulphide through the filtrate. No darkening should be obtained.

*Mercurous Nitrate* is formed when metallic mercury dissolves in dilute nitric acid.

## Mercuric Compounds

*Mercuric Oxide* may be obtained as a red powder by heating mercury in air, or by heating a mixture of mercury and mercuric nitrate.

$$2Hg + O_2 = 2HgO$$
$$Hg(NO_3)_2 + Hg = 2HgO + 2NO_2$$

When obtained by precipitation from solution by addition of sodium hydroxide to a solution of a mercuric salt, it is deposited as a yellow powder. This is the official form. It is chemically rather more active than the red form.

Mercuric oxide decomposes into mercury and oxygen on heating. It reacts with ammonia to form explosive substances, which on drying are converted to the base ($NHg_2OH$) corresponding to dimercuricammonium chloride.

The hydroxide corresponding to mercuric oxide is unknown.

*Mercuric Chloride* is obtained either by reaction of the metal with chlorine, or by subliming mercuric sulphate with sodium chloride (usually a little manganese dioxide or other oxidizing agent is added to prevent the formation of mercurous chloride).

$$Hg + Cl_2 = HgCl_2$$

$$HgSO_4 + 2NaCl = HgCl_2 + Na_2SO_4$$

Mercuric Chloride is a soluble white powder. It is officially assayed by reduction to mercury with an alkaline solution of formaldehyde in presence of potassium iodide. After reduction the solution is acidified (to prevent loss of iodine by reaction with the alkali), and the mercury formed is determined by reaction with iodine (the excess formaldehyde does not react with iodine in acid solution). Excess standard iodine is added, and the excess is determined by back titration with sodium thiosulphate.

$$HgCl_2 + HCHO + 3NaOH$$

$$= Hg + HCOONa + 2NaCl + 2H_2O$$

$$Hg + I_2 + 2KI = K_2HgI_4$$

When ammonia is added to mercuric chloride solution, a white precipitate is thrown down of *mercuricammonium chloride* (*ammoniated mercury*).

$$2NH_3 + HgCl_2 = NH_2HgCl + NH_4Cl$$

This substance may be regarded as a derivative of ammonium chloride in which two atoms of hydrogen have been replaced by an atom of mercury. Ammoniated mercury is decomposed by alkalis and potassium iodide. The reaction with potassium iodide is used for the official assay of Ammoniated Mercury.

The liberated alkali is determined by titration with standard hydrochloric acid.

$$NH_2HgCl + 4KI + H_2O = K_2HgI_4 + KCl + KOH + NH_3$$

On heating with water, ammoniated mercury is converted into dimercuricammonium chloride ($NHg_2Cl$).

A third mercury derivative of ammonium chloride [fusible white precipitate, $HgCl_2$, $2NH_3$ or $Hg(NH_3Cl)_2$] is obtained as a precipitate when mercuric chloride is added to a boiling solution of ammonium chloride and ammonia.

*Mercuric Iodide* is precipitated when potassium iodide is added to mercuric chloride solution. The first precipitate is yellow, but it quickly changes to red. (Mercuric iodide crystallizes in two forms, the red form being the more stable at atmospheric temperatures.) It dissolves readily in excess potassium iodide solution, forming a colourless solution which contains the complex potassium mercuri-iodide.

$$HgCl_2 + 2KI = HgI_2 + 2KCl$$
$$HgI_2 + 2KI = K_2HgI_4$$

This salt (in which the mercury is in the anion) is very stable, and it does not give the ordinary reactions for mercury. It is a valuable analytical reagent (cf. p. 576). In alkaline solution (Nessler's reagent), it is used to detect traces of ammonia (p. 149), aldehydes, and ketones (p. 345).

*Mercuric Cyanide,* which is obtained by reacting on mercuric oxide with potassium cyanide or Prussian blue, is noticeable for its non-ionic character. It forms a non-conducting solution in water, and gives few of the ordinary reactions of mercuric salts and cyanides. Mercuric cyanide decomposes on heating with evolution of cyanogen.

$$Hg(CN)_2 = Hg + (CN)_2$$

Mercuric cyanide reacts with mercuric oxide in presence of water to form basic salts. The official *Mercuric Oxycyanide* has the approximate composition $HgO, 3Hg(CN)_2$. It is assayed for mercuric oxide and mercuric cyanide. The oxide content of the sample can be determined by direct titration with standard hydrochloric acid, which does not react with the mercuric cyanide owing to its non-ionic character. If the titration is continued after the addition of potassium iodide the cyanide can also be determined, for the potassium iodide converts the mercuric cyanide into potassium cyanide, and potassium cyanide can be titrated directly with strong acids.

$$HgO + 2HCl = HgCl_2 + H_2O$$
$$Hg(CN)_2 + 4KI = K_2HgI_4 + 2KCN$$
$$2KCN + 2HCl = 2KCl + 2HCN$$

*Mercuric Thiocyanate* is insoluble in dilute nitric acid. Mercuric salts can therefore be determined by titration with ammonium thiocyanate (using a ferric salt solution as indicator, cf. p. 121).

$$2NH_4CNS + Hg(NO_3)_2 = 2NH_4NO_3 + Hg(CNS)_2$$

*Mercury Fulminate* is isomeric with mercuric cyanate [$Hg(CNO)_2$]. It is prepared for use as a detonator by reacting on mercury with a mixture of nitric acid and alcohol.

*Mercuric Sulphide* is insoluble and is used for the gravimetric determination of mercuric compounds.

*Mercuric Sulphate* is obtained by heating mercury with concentrated sulphuric acid. It is used in the manufacture of other mercury salts, and as a catalyst in the conversion of acetylene to acetaldehyde (p. 377) and the oxidation of naphthalene to phthalic acid (p. 325).

*Mercuric Nitrate* is obtained by dissolving mercury in excess nitric acid, or by reacting with nitric acid on mercuric oxide. In mercuric nitrate ointment, the mercury is present partly as a compound with the fatty base.

*Mercuric Oleate* is the chief constituent of Oleated Mercury B.P., which is prepared by the reaction of mercuric oxide on oleic acid in presence of liquid paraffin.

## Determination of Mercury

Mercury is determined gravimetrically by precipitation as sulphide. The precipitate is collected, washed, dried at 120°C and weighed. Officially this method is used for the assay of mercury in Oleated Mercury, and (after destroying the organic matter by boiling with nitric and sulphuric acids) Strong Mercuric Nitrate Ointment.

The volumetric determination depends on the reaction of mercuric salts with ammonium thiocyanate solution. This method is used officially for the assay of Mercury, Mercury with Chalk, Mercuric Oxide, Mercury Pill, the Mercury Ointments, Dilute Ointment of Mercuric Nitrate and the organic compounds of mercury (p. 533). When necessary, the mercury is first removed from the organic material.

## CHROMIUM

The chief source of chromium compounds is the mineral chromite or chrome ironstone, which is a ferrous chromite of the formula $FeCr_2O_4$. When this ore is reduced by carbon in an electric furnace an iron chromium alloy is obtained, which is used in the manufacture of chromium steels. To obtain the chromium compounds, the ore is first converted into potassium dichromate (p. 285).

Chromium is a metal which resembles iron in its physical properties. It retains a bright lustre in the air (due to a very thin coating of oxide which forms on the metal and protects it from further attack). It is therefore used for chromium plating. (The metal is deposited electrolytically from an acidified solution of potassium dichromate.)

The alloys of chromium with iron are characterized by great hardness, even at red heat (high-speed tool steels). They are also stainless. The alloy of nickel and chromium (nichrome) is used as a resistance wire for winding electric furnaces.

### Compounds of Chromium

Chromium forms three classes of compounds in which its valencies are two, three, and six respectively.

*Chromous Oxide* ($CrO$) is basic, and forms chromous salts which are powerful reducing agents and absorb oxygen from the air. They are prepared by reduction of the chromic salts by hydrogen.

*Chromic Oxide* ($Cr_2O_3$) is amphoteric, and forms salts with acid and alkalies. The corresponding hydroxide dissolves in acids to form the chromic salts, and in strong alkalis forming chromites (e.g. $KCrO_2$) which are easily hydrolyzed. Some chromites occur in nature, e.g. ferrous chromite ($FeO, Cr_2O_3$; $FeCr_2O_4$), but the chromic salts are more important.

Chromic oxide is the most stable oxide of chromium. It is obtained (for use as a pigment) as a green powder by igniting ammonium dichromate or a mixture of potassium dichromate and ammonium chloride.

$$(NH_4)_2Cr_2O_7 = Cr_2O_3 + N_2 + 4H_2O$$

The chromic salts are usually obtained by reduction of chromates or dichromates. The most important salt is the double potassium chromium sulphate, *chrome alum* [$K_2SO_4$, $Cr_2(SO_4)_3$, $24H_2O$] which is obtained when potassium dichromate is reduced with sulphur dioxide. Chrome alum crystallizes in violet octahedra.

$$K_2Cr_2O_7 + H_2SO_4 + 3SO_2 = K_2SO_4 + Cr_2(SO_4)_3 + H_2O$$

*Chromium Trioxide* ($CrO_3$) is an acid oxide, which forms a series of salts derived from chromic acid ($H_2CrO_4$). The chromates are often isomorphous with the sulphates. In addition to normal chromates, chromium trioxide also forms dichromates derived from the acid $H_2Cr_2O_7$, i e. $H_2O$, $2CrO_3$ (compare pyrosulphuric acid $H_2S_2O_7$). The dichromates are more stable than the chromates especially in acid solutions.

Chromium trioxide is obtained by the reaction of potassium dichromate and concentrated sulphuric acid.

$$K_2Cr_2O_7 + H_2SO_4 = K_2SO_4 + 2CrO_3 + H_2O$$

It is precipitated from solution in the form of dark red needles. The adhering sulphuric acid can be removed by dissolving in water, adding barium chromate, filtering, and recrystallizing.

Chromium trioxide is often called "chromic acid," but a true chromic acid ($H_2CrO_4$) can be obtained by crystallizing an aqueous solution of the oxide at a low temperature. It readily loses water and the anhydride is the more stable form.

Chromium trioxide readily loses oxygen on warming, and is converted to the insoluble chromic oxide. Certain impurities (e.g. potassium salts) in Chromium Trioxide B.P. are controlled officially by igniting, extracting the residue with hot water, filtering, and evaporating to dryness.

Chromium trioxide, the chromates, and the dichromates are powerful oxidizing agents. Chromium Trioxide is officially assayed by means of its oxidizing action. Iodine is liberated from an acidified solution of potassium iodide, and titrated with a standard solution of sodium thiosulphate. The salts of chromic acid can be determined similarly, and potassium dichromate solutions for volumetric analysis are sometimes standardized in this way.

$$4CrO_3 = 2Cr_2O_3 + 3O_2$$

$$2CrO_3 + 6KI + 6H_2SO_4 = 3K_2SO_4 + Cr_2(SO_4)_3 + 6H_2O + 3I_2$$

*Potassium Dichromate* is prepared from chrome iron ore by heating it in presence of air with a potassium salt (potassium carbonate, sulphate or potash felspar).

$$4FeCr_2O_4 + 8K_2CO_3 + 7O_2 = 2Fe_2O_3 + 8K_2CrO_4 + 8CO_2$$

After cooling, the product is broken up, and the potassium chromate is separated from the insoluble matter by dissolving in water. On adding sulphuric acid to the solution the less soluble potassium dichromate crystallizes. It is purified by recrystallization from water.

$$2K_2CrO_4 + H_2SO_4 = K_2Cr_2O_7 + K_2SO_4 + H_2O$$

Another process converts the chrome iron ore into calcium chromate by heating it in presence of air with chalk, and potassium dichromate is formed by addition of potassium carbonate to calcium dichromate solution.

Potassium dichromate crystallizes in red crystals. It decomposes when heated strongly.

$$4K_2Cr_2O_7 = 2Cr_2O_3 + 4K_2CrO_4 + 3O_2$$

Potassium dichromate is a strong oxidizing agent, the sexavalent chromium being reduced to the tervalent state.

$$K_2Cr_2O_7 + 4H_2SO_4 = K_2SO_4 + Cr_2(SO_4)_3 + 4H_2O + 3O$$

It is used as an oxidizing agent in organic chemistry (e.g. oxidation of alcohols to aldehydes) and as a reagent in volumetric analysis. For this latter purpose it has advantages over potassium permanganate as it can be used in presence of chlorides and some organic substances. When titrating ferrous salts with potassium dichromate, potassium ferricyanide (which gives a blue colour with ferrous salts but not with ferric salts) may be used as an external indicator.

Potassium dichromate can also be used with internal indicators, although the green colour of the chromic salts formed on reduction tends to obscure their colour changes.

The limit test for chromium in Menaphthone depends on the violet colour given by dichromates with diphenyl carbazide. The test depends on the oxidation of the organic reagent.

*Potassium Chromate* is obtained as the intermediate product in the formation of potassium dichromate. It can also be prepared by the addition of alkali to a solution of potassium dichromate.

$$K_2Cr_2O_7 + 2KOH = 2K_2CrO_4 + H_2O$$

Acids convert the chromates into the dichromates. While potassium chromate is more soluble than potassium dichromate, sodium chromate is less soluble than sodium dichromate. The insolubility of the barium and lead chromates enables small traces of the corresponding metals to be detected. These salts are used commercially as pigments.

*Derivatives of Chromic Acid.* The acid chloride of chromic acid *chromyl chloride* ($CrO_2Cl_2$) is obtained by heating potassium dichromate with sodium chloride and concentrated sulphuric acid. It is a red liquid (in appearance resembling bromine). Like other acid chlorides it is hydrolyzed by water.

$$CrO_2Cl_2 + 2H_2O = H_2CrO_4 + 2HCl$$

*Perchromic Acid.* The addition of hydrogen peroxide to a solution of chromium trioxide results in a blue-coloured compound (possibly perchromic acid $HCrO_5$) which is soluble in ether. The formation of this substance is used as a test for chromates and for hydrogen peroxide.

## TITANIUM

Titanium is a comparatively abundant element (igneous rocks contain about 0·8 per cent of titanium oxide). The chief sources of titanium compounds are ilmenite ($FeTiO_3$) and the various crystalline forms of titanium dioxide ($TiO_2$).

Titanium forms compounds in which its valency is two, three, or four. The bi- and tervalent oxides are basic, but the quadrivalent oxide is amphoteric. (The other metals in the same sub-group of the Periodic Table as titanium are quadrivalent only.)

Owing to the ease with which the tervalent titanous compounds can be oxidized to the quadrivalent state, they are powerful reducing agents. Titanous chloride is used as a volumetric reagent for the determination of iron, as it reduces ferric salts quantitatively to ferrous salts. It is also used for the determination by reduction of certain organic compounds including nitro compounds and certain dyestuffs. Titanous chloride is prepared by electrolytic reduction of titanic chloride in presence of hydrochloric acid. Its solution absorbs oxygen from the air. It must be stored in an atmosphere of hydrogen or carbon dioxide. This is effected by titrating from an apparatus as illustrated in Fig. 25.

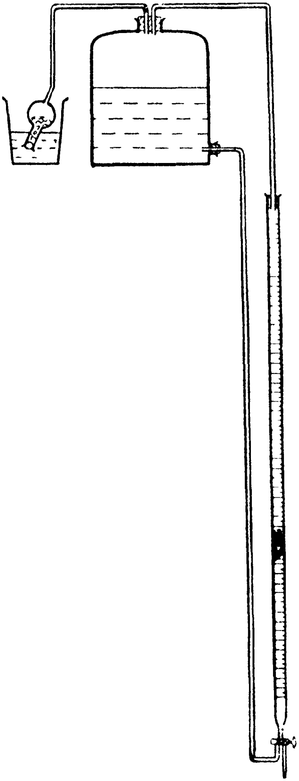


FIG. 25. APPARATUS FOR TITANOUS CHLORIDE TITRATIONS

The air in the titration flask must be replaced by carbon dioxide. For this purpose a little sodium bicarbonate may be added to the reaction mixture before the titration is commenced. When determining ferric salts, the titanous chloride solution is run in until the red colour given by ammonium thiocyanate with ferric salts disappears.

$$TiCl_3 + FeCl_3 = FeCl_2 + TiCl_4$$

Methylene Blue, Brilliant Green, Crystal Violet and Menaphthone are assayed with titanous chloride solution, either by direct titration or by adding excess of the reducing agent and back titrating with ferric ammonium sulphate.

## THORIUM

Although its valency is four, thorium shows a resemblance to the tervalent rare earth elements with which it occurs.

Incandescent gas mantles are made of thoria ($ThO_2$) containing a little ceria ($Ce_2O_3$).

## VANADIUM

Vanadium is a metal which is chiefly used as a constituent of special steels. Vanadium steel has a high tensile strength and is resistant to fatigue, i.e. it does not break easily when subjected to rapid changes in form. It is used for springs.

Vanadium forms compounds with a wide range of valencies, the more important being two, three, and five. The vanadates are derived from the highest oxide ($V_2O_5$) (e.g. ammonium vanadate $NH_4VO_3$, which is a powerful oxidizing agent).

## MOLYBDENUM

Molybdenum occurs as a sulphide $MoS_2$, which when oxidized forms the oxide $MoO_3$, which reacts with ammonia to form ammonium molybdate.

Molybdenum trioxide forms many complex salts derived from acids $MoO_3$; $xH_2O$, where $x$ may be as large as ten.

Ammonium molybdate ($6NH_3$, $7MoO_3$, $7H_2O$) is used for the detection of phosphates, with which, in presence of nitric acid, it forms yellow phosphomolybdic acid ($H_3PO_4$, $12MoO_3$, $24H_2O$).

## TUNGSTEN

Tungsten is used as a constituent of high-speed tool steels, and for electric lamp filaments.

The most important compounds are the tungstates. Sodium tungstate is represented by the formula $Na_2WO_4$, $2H_2O$. It also forms more complex tungstates and phosphotungstates.

## URANIUM

Uranium occurs in the form of its oxide ($U_3O_8$) in pitchblende. Its chief compounds are the uranyl salts in which the metal is sexavalent. In these salts the bivalent uranyl radical containing oxygen ($UO_2$) replaces a single metallic atom, e.g. $(UO_2)Cl_2$; $(UO_2)SO_4$. Uranyl acetate forms double salts with zinc and nickel, which are used for the detection and determination of sodium compounds, since sodium zinc (or nickel) uranyl acetate is insoluble.

$$\begin{aligned}NaCl + 3(UO_2)\,(C_2H_3O_2)_2 + Zn(C_2H_3O_2)_2 + C_2H_4O_2\\ = HCl + NaZn(UO_2)_3\,(C_2H_3O_2)_9\end{aligned}$$

Uranium and the artificial elements of higher atomic number are now regarded as part of a second group of rare earth elements which starts with actinium.

## MANGANESE

Manganese is an element which is distributed widely in small quantities. During the weathering of igneous rocks, the manganese is removed with the iron in the form of a bicarbonate. On oxidation it is precipitated as manganese dioxide, which is the chief ore of manganese (pyrolusite). The metal is usually isolated in the form of ferro-manganese (an alloy with iron) by reducing a mixture of iron and manganese ores in a blast furnace. Ferro-manganese is used as a deoxidizer during the manufacture of steel from cast iron. Manganese steels are very hard and resistant to wear.

Manganese is a fairly reactive metal. It forms compounds covering a wide range of valency (two, three, four, six, and seven). Manganous oxide ($MnO$) is a strong base dissolving in acids to form the manganous salts. Manganic oxide ($Mn_2O_3$) is feebly basic, and forms the unstable manganic salts. Manganese dioxide ($MnO_2$), which is the most stable oxide at low temperatures and in neutral solutions, is an amphoteric oxide. It forms unstable salts with acids and alkalis (e.g. $MnCl_4$ and $CaMnO_3$). Manganese trioxide ($MnO_3$) is an acid-forming oxide which reacts with alkalis to form the manganates (e.g. $K_2MnO_4$). Manganese heptoxide ($Mn_2O_7$) is an acid oxide corresponding to the permanganates (e.g. $KMnO_4$). A sixth oxide ($Mn_3O_4$) is the most stable oxide at high temperatures. It is similar in composition to the magnetic oxide of iron.

### Compounds of Manganese

*Manganous Salts* are the most stable compounds of manganese in acid solution. They are obtained by reduction of the higher valency compounds in acid solution. The manganous ion is very pale pink in colour.

*Manganese Dioxide* is obtained in a hydrated form by the reduction of permanganates in neutral solution, or exposure of manganous hydroxide to air. It is an oxidizing agent.

*Manganates* are prepared by oxidizing manganese dioxide (pyrolusite) by fusing it with alkali in presence of air or an added oxidizing agent.

$$4KOH + 2MnO_2 + O_2 = 2K_2MnO_4 + 2H_2O$$

When the mass is cool, the manganates may be dissolved out in water. Manganates form green crystals. In solution, they are not very stable, and in presence of acid they are converted to a mixture of permanganate and manganese dioxide.

$$3K_2MnO_4 + 2H_2O = 2KMnO_4 + MnO_2 + 4KOH$$

*Potassium Permanganate* is prepared from potassium manganate by adding acid or by oxidation by air or chlorine.

$$4K_2MnO_4 + 2H_2O + O_2 = 4KMnO_4 + 4KOH$$

Potassium permanganate crystallizes from water in violet crystals. It is a powerful oxidizing agent, and is used as a volumetric reagent for the titration of reducing agents. The titration is carried out in sulphuric acid solution. As the permanganate is reduced to form an almost colourless manganous salt, no further indicator is necessary to determine the end-point.

$$2KMnO_4 + 3H_2SO_4 = K_2SO_4 + 2MnSO_4 + 3H_2O + 5O$$

Potassium Permanganate is officially assayed by titration against oxalic acid, which is quantitatively oxidized on warming.

$$H_2C_2O_4 + O \qquad H_2O + 2CO_2$$

In alkaline solution, permanganates are reduced only to the manganates. In neutral solutions, manganese dioxide is formed.

$$2KMnO_4 + 2KOH = 2K_2MnO_4 + H_2O + O$$

$$2KMnO_4 = K_2O + 2MnO_2 + 3O$$

Before carrying out the official limit tests for sulphate or chloride on Potassium Permanganate, it is reduced in neutral solution by alcohol. The precipitated manganese dioxide is removed by filtration and the colourless filtrate is used for the limit tests.

Permanganic acid ($HMnO_4$) and permanganic anhydride ($Mn_2O_7$) have been prepared. They are very unstable substances.

### Determination of Manganese

Manganese can be determined gravimetrically by conversion into the oxide ($Mn_3O_4$), or volumetrically by oxidation to permanganate and titration with oxalic acid.

## IRON, COBALT, AND NICKEL

Iron, cobalt, and nickel have very nearly the same atomic weights, and the properties of the elements and their compounds are similar. The three elements were placed by Mendeléef into a single place in his Periodic Table. The three metals exist in magnetic and non-magnetic forms. Their valencies are two and three, but the stability of the tervalent compounds diminishes from iron to nickel (the latter element forms no stable tervalent salts). Many stable complex compounds are formed by these elements.

## IRON

Iron is the second most abundant metal in the earth's crust. The ferrous and ferric silicates, which occur in igneous rocks, are decomposed during weathering, the iron being dissolved as ferrous bicarbonate. This is converted by oxidation into deposits of hydrated ferric hydroxide. Afterwards these deposits may be partially dehydrated to form the important deposits of haematite ($Fe_2O_3$). Magnetic oxide of iron ($Fe_3O_4$) is another important ore. Iron pyrites and marcasite ($FeS_2$) are sources of sulphur compounds.

### Properties of Iron

Iron is a grey metal, which crystallizes in several different forms. The ordinary magnetic form ($\alpha$ iron) is stable up to 760°C. Above this temperature other non-magnetic forms are stable. Iron B.P. is bright iron wire.

Iron is a reactive metal. It dissolves readily in dilute acids evolving hydrogen. It rusts in moist air, i.e. it changes to a hydrated ferric hydroxide. The process is a complex one and is not fully explained by the equations usually given—

$$Fe + 2H_2CO_3 = Fe(HCO_3)_2 + H_2$$

$$4Fe(HCO_3)_2 + O_2 + 2H_2O = 4Fe(OH)_3 + 8CO_2$$

Iron rust does not protect the surface of the metal from further attack, but by dipping iron in concentrated nitric acid a more coherent film of oxide can be formed, and this film does protect the underlying metal so that it becomes non-reactive and *passive*.

Iron is bivalent or tervalent in its compounds. [Magnetite ($Fe_3O_4$) which is the most stable oxide of iron at high temperatures is probably a compound of ferrous and ferric oxides (ferrous ferrite). Iron pyrites and marcasite are abnormal compounds in that they have the formula $FeS_2$. Marcasite is the less stable form and oxidizes readily to ferrous sulphate. Many important minerals (e.g. copper pyrites) are derivatives of iron pyrites or marcasite.]

Ferrous hydroxide is a stronger base than ferric hydroxide, so that the ferrous salts are less easily hydrolyzed than the ferric salts. Ferrous salts are easily oxidized to the ferric state, while conversely ferric salts are easily reduced. These oxidations and reductions enable iron salts to be determined by volumetric methods.

## Ferrous Compounds

*Ferrous Oxide* is obtained by the action of heat on ferrous oxalate, or by partial reduction of ferric oxide.

$$FeC_2O_4 = FeO + CO_2 + CO$$

It is easily oxidized to ferric oxide. Ferrous hydroxide is obtained in absence of air as a white precipitate by precipitation from ferrous salt solutions. It is readily oxidized.

*Ferrous Sulphate* is formed by the weathering of marcasite, or by dissolving iron in dilute sulphuric acid.

$$2FeS_2 + 2H_2O + 7O_2 = 2FeSO_4 + 2H_2SO_4$$

$$Fe + H_2SO_4 = FeSO_4 + H_2$$

It crystallizes from aqueous solution with seven molecules of water of crystallization ($FeSO_4$, $7H_2O$) as green crystals, which may become brown owing to superficial oxidation. A pentahydrate ($FeSO_4$, $5H_2O$) is also formed which is isomorphous with crystalline copper sulphate, and is a common impurity in that substance.

When ferrous sulphate crystals are gently heated, water is driven off, but if the drying is carried out at an excessive temperature, or if too much water is removed, considerable oxidation and hydrolysis take place and an appreciable quantity of basic ferric sulphate is formed.

The official *Exsiccated Ferrous Sulphate* is dried at 40°C until it contains the equivalent of not less than 77 per cent of the anhydrous salt. (This proportion corresponds approximately with the composition $FeSO_4, 2H_2O$.) The quantity of basic salt formed during the exsiccation is controlled by the stipulation that 2 g must dissolve completely in 7·5 mils of boiled and cooled water (to avoid oxidation by dissolved oxygen) containing 0·5 mil N sulphuric acid.

When ferrous sulphate is strongly heated it is completely decomposed.

$$2FeSO_4 = Fe_2O_3 + SO_3 + SO_2$$

*Ferrous Ammonium Sulphate* [$FeSO_4$, $(NH_4)_2SO_4$, $6H_2O$] is sometimes used as a reagent for the standardization of solutions of oxidizing agents.

*Ferrous Chloride* is obtained by dissolving iron in hydrochloric acid.

*Ferrous Iodide* is obtained by direct union of metallic iron and iodine.

$$Fe + I_2 = FeI_2$$

*Ferrous Carbonate* occurs in rust and some natural iron ores. It can be obtained by precipitation from a ferrous salt with sodium carbonate, but under these conditions it tends to oxidize. The oxidation may be hindered by precipitation in the presence of liquid glucose as for the preparation of Saccharated Iron Carbonate B.P. The ferrous iron present in this preparation and in Pill of Iron Carbonate is determined officially by dissolving in sulphuric acid and titrating with potassium iodate solution in presence of hydrochloric acid Potassium permanganate could not be used owing to the presence of reducing sugars. These also react (although to a smaller extent) with potassium dichromate.

The method corresponds to the reaction

$$KIO_3 + 4FeCl_2 + 6HCl = 4FeCl_3 + KCl + ICl + 3H_2O$$

However, the process really involves the use of iodine monochloride as an oxidizing agent, and this substance is added prior to the titration. Iodine is liberated from its reaction on the ferrous salt, and the iodate reconverts this iodine back to iodine monochloride, the end-point corresponding to the complete reconversion of the liberated iodine.

$$4FeCl_2 + 4ICl = 4FeCl_3 + 4I$$
$$KIO_3 + 4I + 6HCl = KCl + 3H_2O + 5ICl$$

*Ferrous Phosphate* is obtained by dissolving the metal in phosphoric acid. *Compound Syrup of Ferrous Phosphate* is assayed for iron by oxidation to the ferric state, and titration with titanous chloride. The oxidation is carried out by adding potassium permanganate until the colour just persists. Concentrated hydrochloric acid is added, and after the air is displaced from the apparatus by adding a little sodium bicarbonate to the solution, the solution is titrated with titanous chloride using the apparatus shown in Fig. 25, p. 287.

The iron is probably present in this syrup as acid ferrous phosphate [$Fe(H_2PO_4)_2$].

## Ferric Compounds

*Ferric Hydroxide* is precipitated when ammonia is added to a solution of a ferric salt. On heating it is transformed to ferric oxide.

$$FeCl_3 + 3NH_4OH = 3NH_4Cl + Fe(OH)_3$$
$$2Fe(OH)_3 = Fe_2O_3 + 3H_2O$$

Ferric oxide is reduced to a fine metallic powder (reduced iron) by heating in an atmosphere of hydrogen at a temperature of 500–600°C.

*Ferric Chloride* is obtained by the direct union of iron and chlorine. The anhydrous compound (which is easily vaporized) possesses the formula $Fe_2Cl_6$. It is very soluble in water, with which it forms several hydrates. (The hydrates cannot be converted into the anhydrous salt without hydrolysis.) Solution of Ferric Chloride B.P. is obtained by dissolving iron in hydrochloric acid, and oxidizing the ferrous chloride formed by chlorine or nitric acid.

$$2FeCl_2 + Cl_2 = 2FeCl_3$$

The solution is acid and more stable than neutral solutions of ferric chloride which tend to hydrolyze and deposit ferric hydroxide.

$$FeCl_3 + 3H_2O = Fe(OH)_3 + 3HCl$$

If made from scrap iron containing brass, copper or zinc would be present in the solution. It is stipulated that after removing the iron by precipitation with ammonia, the official solution should not form a precipitate with potassium ferrocyanide.

*Ferric Sulphate* is usually prepared in the form of its alums, $K_2SO_4$, $Fe_2(SO_4)_3$, $24H_2O$, and $(NH_4)_2SO_4$, $Fe_2(SO_4)_3$, $24H_2O$.

*Ferric Thiocyanate* possesses a blood red colour which is used as a sensitive test for the presence of iron and thiocyanates (e.g. as an indicator in the determination of halides by silver nitrate—ammonium thiocyanate titration).

*Iron and Ammonium Citrate B.P.* is a complex salt whose exact composition varies with the conditions of preparation. The reactions for citrates and iron are not given clearly until the complex has been broken up (by heating with sodium hydroxide solution, or ignition to ferric oxide respectively).

The official assay is based on the oxidizing action of ferric salts, which liberate iodine from a strongly acid solution of potassium iodide.

$$2FeCl_3 + 2KI = 2FeCl_2 + 2KCl + I_2$$

The sample is warmed with concentrated sulphuric acid (to break up the complex) and any ferrous iron is oxidized to the ferric state by adding potassium permanganate solution until the colour persists for a short time. Potassium iodide and concentrated hydrochloric acid are then added, and the liberated iodine is found by thiosulphate titration.

## Determination of Iron

Iron is determined gravimetrically by precipitation as ferric hydroxide, and after ignition weighing as ferric oxide. This method is used for the official assay of Solution of Ferric Chloride.

Volumetrically, iron is determined by taking advantage of the ease of conversion of ferrous into ferric salts, and *vice versa*. Ferrous salts may be determined by titrating with an oxidizing agent. Potassium permanganate may be used in absence of chlorides and interfering organic substances, e.g. as in the official assay of Ferrous Sulphate, otherwise reagents such as potassium dichromate, ceric sulphate, or iodine monochloride are used.

Ferric salts may be determined by reducing them to the ferrous state, and titrating as above. They can also be determined on their oxidizing power either by liberation of iodine from an iodide as for the official assay of Iron and

Ammonium Citrate, or by titration with titanous chloride as for the official assay of Compound Syrup of Ferrous Phosphate.

## Complex Compounds of Iron

Iron forms many complex compounds, the most important being the salts of ferrocyanic acid [$H_4Fe(CN)_6$] and ferricyanic acid [$H_3Fe(CN)_6$]. These complex cyanides are obtained by reaction of excess of a soluble cyanide with ferrous or ferric salts respectively. Thus when potassium cyanide is added to ferrous sulphate solution ferrous cyanide is formed, and this combines with excess potassium cyanide to form potassium ferrocyanide.

$$FeSO_4 + 2KCN = Fe(CN)_2 + K_2SO_4$$
$$Fe(CN)_2 + 4KCN = K_4Fe(CN)_6$$

*Potassium Ferrocyanide* may be prepared from waste nitrogenous organic matter by heating with potash and metallic iron. After heating, the potassium ferrocyanide is washed out in water.

It is obtained from the *spent oxide* of the gas-works. The nitrogen in coal is converted during the manufacture of coal gas into hydrogen cyanide, which is removed from the gas together with the sulphur by passing it over iron oxide. The exhausted or *spent* iron oxide is treated with lime, when calcium ferrocyanide is formed and is extracted in water. (The spent oxide contains Prussian blue which is decomposed by lime.)

$$Fe(OH)_2 + 2HCN = Fe(CN)_2 + 2H_2O$$
$$Fe(OH)_3 + 3HCN = Fe(CN)_3 + 3H_2O$$
$$3Fe(CN)_2 + 4Fe(CN)_3 = \underset{\text{Prussian blue}}{Fe_4[Fe(CN)_6]_3}$$
$$Fe_4[Fe(CN)_6]_3 + 6Ca(OH)_2 = 3Ca_2[Fe(CN)_6] + 4Fe(OH)_3$$

Calcium ferrocyanide is converted into the potassium salt by addition of potassium carbonate.

It is possible to remove hydrogen cyanide and ammonia together from coal gas by passing it through ferrous sulphate solution. Ammonium ferrocyanide is formed at first, and is then converted to ferrous ferrocyanide, which may be treated with lime as above.

Potassium ferrocyanide crystallizes from water as yellow crystals. It is a very stable complex salt, and gives none of the ordinary reactions for iron. Correspondingly it differs from the cyanides in being non-poisonous.

The corresponding complex acid (ferrocyanic acid) can be obtained as a white precipitate by the addition of concentrated hydrochloric acid to potassium ferrocyanide solution.

Many of the metals form precipitates of insoluble ferrocyanides when potassium ferrocyanide is added to a solution of their salts. Many metals may be detected by the formation of these precipitates. Ferric ferrocyanide, which is obtained as a blue precipitate when a ferric salt is added to potassium ferrocyanide solution, is used as a pigment (Prussian blue). Small quantities of cyanides may be detected by the formation of this substance when a cyanide reacts with ferrous sulphate in alkaline solution, and after acidifying, a ferric salt is added. This test is used officially for detecting cyanides as impurities in iodine, etc. (p. 164), and it is the basis of the test for nitrogen in organic compounds (p. 200).

When potassium ferrocyanide is heated with sulphuric acid, the complex radical is broken up. Dilute sulphuric acid liberates hydrogen cyanide, and the concentrated acid forms carbon monoxide (cf. p. 229).

$$2K_4Fe(CN)_6 + 3H_2SO_4 = 3K_2SO_4 + \underset{\substack{\text{Potassium ferrous}\\ \text{ferrocyanide}}}{FeK_2[Fe(CN)_6]} + 6HCN$$

$$K_4Fe(CN)_6 + 6H_2SO_4 + 6H_2O$$
$$= 2K_2SO_4 + FeSO_4 + 3(NH_4)_2SO_4 + 6CO$$

*Potassium Ferricyanide* is formed by the oxidation of potassium ferrocyanide with chlorine.

$$2K_4Fe(CN)_6 + Cl_2 = 2K_3Fe(CN)_6 + 2KCl$$

It forms deep red crystals. It is not so stable as the ferrocyanide, to which it tends to revert. On exposure to light, the crystals of potassium ferricyanide become coated with a layer of the ferrocyanide. Potassium ferricyanide is an oxidizing agent.

$$2K_3Fe(CN)_6 + 2KOH = 2K_4Fe(CN)_6 + H_2O + O$$

The cyanide radicals in ferrocyanides and ferricyanides may be replaced by other radicals, e.g. by replacing one of the cyanide groups of sodium ferricyanide by the nitrosyl group (NO) *sodium nitroprusside* $Na_2[FeNO(CN)_5], 2H_2O$ is obtained. This salt is prepared by the action of nitric acid on potassium ferrocyanide, or by the reaction of ferrous sulphate with potassium cyanide and sodium nitrite. Sodium nitroprusside gives a purple colour with small quantities of soluble sulphides (cf. p. 182), and gives a characteristic red colour with acetone in presence of acetic acid.

## COBALT

The chief ores of cobalt are the sulphide and the arsenide. Cobalt is separated from the other metals present in the ores by a wet process. Cobalt metal resembles iron, and is used as a constituent of special steels.

Chemically, cobalt resembles iron, but the cobaltic salts are less stable than the ferric salts. Cobaltous salts are the common salts and are pink in solution (cobalt ion), but are blue when dehydrated. Cobalt salts are used in the manufacture of blue glass. Cobalt forms a large number of stable complex salts, in which the metal is united to various groups and radicals, e.g. potassium cobalticyanide ($K_3Co(CN)_6$), potassium cobaltinitrite ($K_3Co(NO_2)_6$).

## NICKEL

The chief ores of nickel are the sulphide and the arsenide. The iron is removed from these ores by preferential oxidation. The purified nickel ore is then mixed with carbon, and reduced at a fairly low temperature. The metallic nickel is separated from the other metals present by passing carbon monoxide over the reduced product. Nickel forms a volatile carbonyl which distils away, and is decomposed by heating. The nickel is deposited and the carbon monoxide is liberated.

$$Ni + 4CO \rightleftharpoons Ni(CO)_4$$

Nickel is a white metal, which is more resistant to attack than iron. Hence it is used for certain laboratory apparatus and for nickel plating. Nickel forms valuable alloys with iron (nickel steel), chromium (nichrome), and with copper and zinc (nickel silver).

Nickel absorbs hydrogen readily, and is a powerful catalyst, especially when finely divided, for reactions involving hydrogenation. For example, it is used for the hydrogenation of carbon disulphide (p. 223), and of fats (p. 402).

Nickel forms only bivalent stable salts. The oxide $Ni_2O_3$ and a few unstable complex compounds are the only examples of tervalent nickel compounds.

## THE PLATINUM METALS

The six platinum metals, Ruthenium, Rhodium, and Palladium, Osmium, Iridium, and Platinum, are white metals of high melting point, which occur together in the metallic form. They are not readily attacked by acids. Their compounds are unstable and easily reduced to the metallic state. They form many complex compounds.

Platinum chloride (really $H_2PtCl_6$) is obtained by dissolving platinum in *aqua regia*. The ammonium and potassium salts of this acid are sparingly soluble in water. Ruthenium red is a complex compound $[Ru4NH_3, Cl, OH]Cl$.

## COMPLEX COMPOUNDS

When ferrous cyanide reacts with potassium cyanide, a compound is obtained which gives none of the ordinary reactions of iron, i.e. the solution of the compound contains no ferrous ions, but the iron is present as the complex ferrocyanide ion.

$$4KCN + Fe(CN)_2 = K_4Fe(CN)_6$$

Potassium ferrocyanide is a typical example of a *complex salt* which dissociates in solution into ions quite different from those of its original components.

$$K_4Fe(CN)_6 \rightleftharpoons 4K^+ + [Fe(CN)_6]^{----}$$

Other salts when mixed together in solution form crystals containing both salts, but the corresponding compound does not seem to exist in solution. For example, a solution containing potassium chloride and magnesium chloride deposits crystals of carnallite ($KCl, MgCl_2, 6H_2O$). But carnallite in solution gives only the ordinary reactions for potassium, magnesium, and chloride. Compounds, like carnallite, which exist only in the solid state, and are decomposed in solution are called *double salts*.

Not all complex salts are as stable as the ferrocyanides, and many are known which are partially decomposed in solution into the original components, e.g. potassium cadmium cyanide.

$$K_2Cd(CN)_4 \rightleftharpoons 2KCN + Cd(CN)_2$$

It seems therefore that there is no sharply defined boundary between complex salts and double salts. The difference is one of degree and not of contrast. The distinction depends on the relative degree of stability of the complex substance formed.

The ordinary valency forces which cause the atoms of the elements to combine to form their ordinary compounds cannot serve to explain the formation of complex compounds such as potassium ferrocyanide or double salts such as carnallite. It is necessary to suppose that further combining tendencies are operative in addition to these usual valency forces, so that the further combination may be rendered possible.

*Werner* (1893) noticed that the composition of the compounds or complex ions which are formed by these attractive forces additional to the ordinary valency forces, is determined by the number of atoms, radicals, or single molecules, which a certain atom may unite to itself.

Werner called this number the *co-ordination number* of the element, and he called compounds formed by attractions other that the usual valency forces *co-ordination compounds*. The co-ordination number of most elements is either four or six; that of iron and cobalt is six, as will be seen from the following formulae—

$K_4[Fe(CN)_6]^{--}$; $K_3[Fe(CN)_6]^{---}$; $Na_2[Fe(CN)_5NO]^{-}$;
Potassium ferrocyanide; Potassium ferricyanide; Sodium nitroprusside

$K_3[Co(CN)_6]^{--}$; $K_3[Co(NO_2)_6]^{--}$
Potassium cobalticyanide; Potassium cobaltinitrite

Werner used the square bracket symbol to differentiate between those atoms or groups united directly (i.e. co-ordinated) to the central atom, and those which are not directly attached but held only by the electrical attractions between the oppositely charged ions (cf. p. 313).

It can be proved in various ways that the groups written inside the brackets are linked directly to the central atom, e.g. by the possibility of stereoisomerism, and by the fact that all the halogen contained in the substance of the formula $[Cr(NH_3)_6]^{+++}Cl_3$ can be precipitated with silver nitrate, but only two-thirds of the halogen content of the compound $[Cr(NH_3)_5Cl]^{++}Cl_2$ can be so precipitated.

The valency of the complex group depends on the relative proportion of acidic and basic groups inside the complex. This may be illustrated by the series of compounds—

(1) $K_3[Co(NO_2)_6]$ (7) $[Co(NH_3)_6]^{+++}Cl_3$
(2) $K_2[Co(NO_2)_5NH_3]^{-}$ (6) $[Co(NH_3)_5NO_2]^{++}Cl_2$
(3) $K[Co(NO_2)_4(NH_3)_2]^{-}$ (5) $[Co(NH_3)_4(NO_2)_2]^{+}Cl$
(4) $[Co(NH_3)_3(NO_2)_3]$
(Neutral and non-ionic)

# CHAPTER XIX

# THE CLASSIFICATION OF THE ELEMENTS

As chemistry developed, it was realized that certain elements were related in their physical and chemical properties, and families of elements were recognized, e.g. the halogen group, and the nitrogen, phosphorus, arsenic, antimony, and bismuth group. It was suspected that the atomic weights of the elements in these families were also related (e.g. the atomic weight of bromine (80) is approximately the mean of the atomic weights of chlorine (35·5) and iodine (127) ).

The first complete scheme which indicated the relationships between the atomic weights and the chemical properties of all the known elements was published in 1869 by Mendeléef. Mendeléef found that if the elements were written down in order of their atomic weights, periodically, at certain intervals, similar chemical properties appeared in the elements. Thus, following hydrogen, the next seven elements known in Mendeléef's time were

| | Lithium | Beryllium | Boron | Carbon | Nitrogen | Oxygen | Fluorine |
|---|---|---|---|---|---|---|---|
| At. Wt. | 7 | 9 | 11 | 12 | 14 | 16 | 19 |

Then follows sodium, which resembles lithium in properties, magnesium which resembles beryllium and so on, thus—

| | Sodium | Magnesium | Aluminium | Silicon | Phosphorus | Sulphur | Chlorine |
|---|---|---|---|---|---|---|---|
| At Wt. | 23 | 24 | 27 | 28 | 31 | 32 | 35·5 |

Chlorine is followed by potassium (39), which resembles sodium, and so on.

This periodicity in properties of the elements when written in the order of their atomic weights was called by Mendeléef the *Periodic Law*.

In the first two periods of Mendeléef's original table (the two short periods considered above), the resemblance in properties recurred every seventh element, but after potassium it was necessary to pass to the seventeenth element for a recurrence of alkali metal properties in rubidium. A similar interval was necessary after rubidium for alkali metal properties to recur with caesium, e.g.*—

| | Potassium | Calcium | Scandium | Titanium | Vanadium | Chromium | Manganese | Iron |
|---|---|---|---|---|---|---|---|---|
| At Wt. | 39 | 40 | 45 | 48 | 51 | 52 | 55 | 56 |

| | Cobalt | Nickel | Copper | Zinc | Gallium | Germanium | Arsenic | Selenium | Bromine |
|---|---|---|---|---|---|---|---|---|---|
| At. Wt. | 59 | 59 | 63·6 | 65·4 | 70 | 72·6 | 75 | 79 | 80 |
| At. Wt. | 85 | Rubidium | | | | | | | |

Mendeléef published his table in the following form. He divided the long periods into two sub-periods (called the *odd* and the *even* series), and placed three elements chemically similar, and of very nearly the same atomic weight in one position in the table. He called these elements the *transition elements.* He justified the division into odd and even series by some valency relationships between the particular elements, e.g. copper, silver, and gold form univalent compounds, and are brought into the same group as the alkali metals; manganese is septavalent in the permanganates as chlorine is in the perchlorates.

The inert gases, which were unknown in Mendeléef's time, have been included in the table opposite, so that it includes the whole of the elements present on the earth's surface. The inert gases form a group of zero valency elements, separating the univalent non-metallic halogens and the univalent alkali

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* Elements which were unknown in Mendeléef's time and for which he left spaces, have been included here.

metals. The maximum valency of the elements in each group increases steadily from zero to seven. The valency towards hydrogen rises to four, and then drops steadily again. These general relationships have also been indicated in the table.

In every vertical group of the Periodic Table, there is a general resemblance in properties but also a gradual change. There is an increase in the metallic character of the element with increase in atomic weight. The lightest element of each group usually differs somewhat from the succeeding members, and resembles the members of the next group; thus, lithium resembles magnesium, beryllium resembles aluminium, and boron resembles silicon in many of their chemical properties. The particular relationships of the elements in the various groups of the Periodic Table have been indicated already.

## Extension of the Transition Series

Mendeléef's Periodic Table which divided the elements into odd and even series and placed three chemically similar elements in a transition series, stressed the similarities rather than the often great differences between the members of the odd and even series, e.g. copper and sodium, manganese and chlorine. A more satisfactory classification is obtained if the transition series is extended to include all the elements whose properties are not very similar to those of the first two elements (the type elements) of each group. Thus the first transition period would be indicated as follows -

*Transition Series*

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| He, | Li, | Be, | | | | | | | | | | | B | C, | N, | O, | F, |
| Ne, | Na, | Mg. | | | | | | | | | | | Al | Si, | P, | S, | Cl, |
| Ar, | K, | Ca, | Sc, | Ti, | V, | Cr, | Mn, | Fe, | Co, | Ni, | Cu, | Zn, | Ga, | Ge, | As, | Se, | Br |

The elements in the extended transition series are not dissimilar in their physical and chemical properties. They are all metals, which form valuable series of alloys with one another (e.g. the steels, and brass). Many of these alloys contain solid solutions (cf. p. 75) of the one metal in the other; i.e. the elements are sufficiently similar for the atom of the one to be capable of replacing an atom of the other in its crystal.

The elements have a common valency of two, although other valencies are also exhibited. The bivalent compounds resemble one another, and are often isomorphous. The existence of these bivalent compounds is not indicated in the older form of the Periodic Table. There are also many similarities between the compounds of valency three. A further resemblance between these elements is their tendency to form complex compounds, many of which are very stable. The complete periodic table in accordance with the extension of the transition series is shown on p. 305.

## The Structure of the Atom

In the Periodic Table as shown facing p. 302, there are a few cases where the order of the elements does not correspond with their atomic weights, e.g. although iodine is related to chlorine and bromine, and tellurium resembles sulphur and selenium, the strict order of the atomic weights would place these elements in the reverse position, i.e. iodine with selenium, and tellurium with bromine.

The chemical properties of an element are determined not so much by its atomic weight as by its *atomic number*. The atomic numbers of the elements increase uniformly by unity from one element to its neighbour in the Periodic Table. The atomic number of hydrogen is unity. The atomic numbers of the elements are shown in the table on p. 305. The atomic numbers can be found experimentally. Their significance is based on the modern conceptions of atomic structure.

It appears that the atoms of all the elements are made up of three fundamental units, the *electron*, which is the unit particle of negative electricity (the mass of the electron is very small), the *neutron*, which is an electrically uncharged particle of mass one on the ordinary atomic weight scale, and the *proton*, which is a particle of the same mass as the neutron, but which carries a positive charge equal in magnitude to the charge on the electron. The mass of an atom is determined by the total number of neutrons and protons contained in it. The number of protons is the same as the number of electrons because the atom is, as a whole, electrically neutral.

It has been found that every atom consists of an extremely small central nucleus, around which are revolving electrons in various orbits. The atom is thus pictured in the form of a miniature solar system. The nucleus contains the whole mass of the atom, and therefore contains all the protons and neutrons in the atom. The electrons revolve around the nucleus. The radius of the outermost electronic orbit constitutes what ordinarily is meant by the radius of the atom. The central nucleus is very much smaller than this and hence the atom is very largely empty.

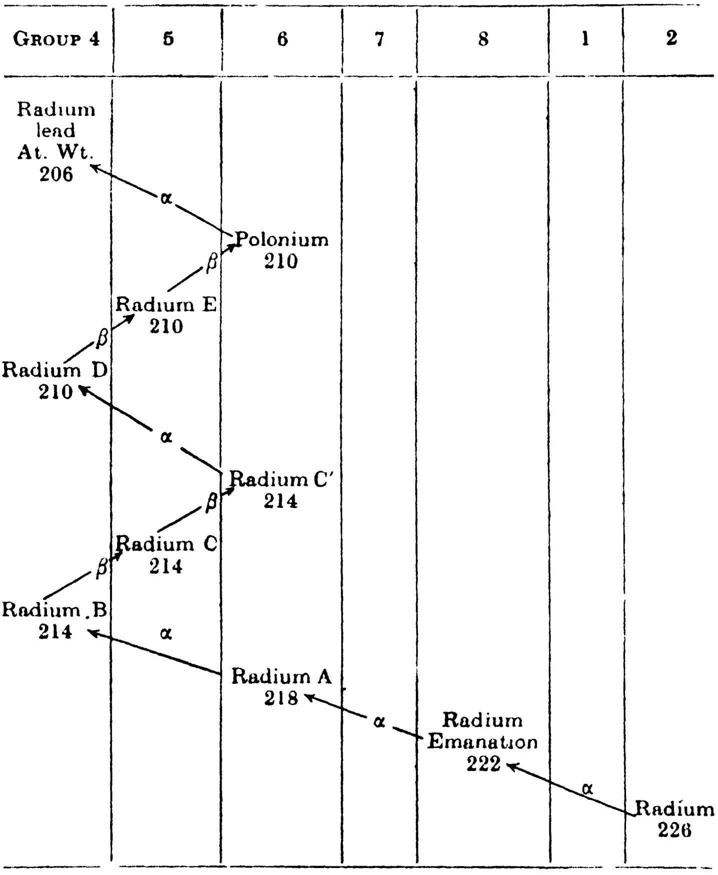
The atomic number of the element is equal to the number of electrons revolving around the atomic nucleus. (This is equal to the total number of unit positive charges on the nucleus.) Hydrogen has one planetary electron, helium two, lithium three, and so on.

Since the chemical properties of the elements depend on their atomic numbers, they are determined by the number of planetary electrons. The existence of *isotopes* is a further illustration of this point. Isotopic atoms have the same number of planetary electrons but different nuclear mass, e.g. the isotopes of lithium have nuclei of mass six and

## PERIODIC TABLE SHOWING EXTENDED TRANSITION SERIES AND ATOMIC NUMBERS

| **Group** | 0 | 1 | 2 | Transition Series | | | | | | | | | | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | H<br>1 |
| | He<br>2 | Li<br>3 | Be<br>4 | | | | | | | | | | | B<br>5 | C<br>6 | N<br>7 | O<br>8 | F<br>9 |
| | Ne<br>10 | Na<br>11 | Mg<br>12 | | | | | | | | | | | Al<br>13 | Si<br>14 | P<br>15 | S<br>16 | Cl<br>17 |
| | A<br>18 | K<br>19 | Ca<br>20 | Sc<br>21 | Ti<br>22 | V<br>23 | Cr<br>24 | Mn<br>25 | Fe<br>26 | Co<br>27 | Ni<br>28 | Cu<br>29 | Zn<br>30 | Ga<br>31 | Ge<br>32 | As<br>33 | Se<br>34 | Br<br>35 |
| | Kr<br>36 | Rb<br>37 | Sr<br>38 | Y<br>39 | Zr<br>40 | Nb<br>41 | Mo<br>42 | Tc<br>43 | Ru<br>44 | Rh<br>45 | Pd<br>46 | Ag<br>47 | Cd<br>48 | In<br>49 | Sn<br>50 | Sb<br>51 | Te<br>52 | I<br>53 |
| | Xe<br>54 | Cs<br>55 | Ba<br>56 | Lanthanides<br>57–71 | Hf<br>72 | Ta<br>73 | W<br>74 | Re<br>75 | Os<br>76 | Ir<br>77 | Pt<br>78 | Au<br>79 | Hg<br>80 | Tl<br>81 | Pb<br>82 | Bi<br>83 | Po<br>84 | At<br>85 |
| | Rn<br>86 | Fr<br>87 | Ra<br>88 | Actinides<br>89–96 | | | | | | | | | | | | | | |

seven respectively, but both have three planetary electrons. Most elements have been found to be mixtures of various isotopes, in proportions which seem to be constant. The large departures from whole



numbers of the atomic weights of certain elements is due to the presence of isotopes; thus, chlorine (At. Wt. 35·5) consists of a mixture of two isotopes (At. Wts. 35 and 37). The isotopes of the elements (with the exception of those of hydrogen (H = 1 and H = 2) are identical in all their chemical and physical properties (except the few properties which depend only on the mass of the atom). Their separation is therefore a matter of great difficulty.

Further illustration of the determination of chemical properties of an element by the number of its planetary electrons depends on the phenomenon of radioactivity. Radioactivity is found mainly among the elements of the highest atomic weights, and most elements beyond lead in the Periodic Table are radioactive. The nuclei of these elements are the most complex of all, so complex that they are unstable. A *radioactive change* occurs when a nucleus of one element breaks down into a nucleus of a simpler element. The new element may itself be unstable, and would then dissociate further.

Radioactive changes are accompanied by the emission of either an *alpha particle* (i.e. a doubly positively charged helium atom $He^{++}$), or a *beta particle* (i.e. an electron). Gamma rays, which correspond to X-rays of very short wave-length, are sometimes emitted as the result of secondary changes. The rate of spontaneous radioactive change of any element is a characteristic constant of that element, and is independent of the state of chemical combination of the element, and the temperature. Apart from their radioactivity, the radioactive elements do not differ from the other elements. They form compounds whose behaviour corresponds with their position in the Periodic Table.

When the nucleus of a radioactive element disintegrates with emission of an alpha particle, the nucleus of the new atom formed has a mass less by four than that of the original atom. Further, the nuclear charge will be less by two units, so that the new nucleus holds around itself two less planetary electrons. The new element lies two places lower in the Periodic Table than the original element, corresponding with the change in the atomic number. When the radioactive change is accompanied by the emission of an electron, the mass is practically unaffected, but the net positive charge on the nucleus of the new element is greater by one than that of the original element. The new element occupies the next place higher in the Periodic Table to that of the original element, also corresponding with the change in the atomic number. These changes are illustrated in the diagram on p 306.

Similar disintegrations of ordinarily non-radioactive elements have been induced by collision with fast moving particles of high energy content (e.g. fast moving hydrogen ions or neutrons). During their decay some artificial radioactive elements emit *positrons*. The positron is a particle of the same mass as the electron and has a positive charge equal in magnitude to the negative charge on the electron.

Many of the products of artificial radioactivity are radioactive isotopes of the normal elements (e.g. radio-phosphorous, radio-iodine). When such radioactive isotopes are mixed with the ordinary elements they cannot be separated by ordinary chemical changes. Thus they can be used to show where the particular element goes during a chemical or biological process, i.e. they can be used as *radioactive indicators* or *tracer elements*.

## The Electronic Interpretation of Chemical Combination

The chemical properties of any element are controlled by the atomic number, i.e. the number of electrons circulating around the nucleus. If chemical combination is due to modifications in the planetary electronic systems of the atoms, the inert gases, which do not enter into any chemical combination, must possess electronic systems of great stability. In the Periodic Table, the inert gases are preceded by the halogens and succeeded by the alkali metals. These families of elements are characterized by their tendency to ionize as univalent electronegative and univalent electropositive ions respectively. The ions formed contain the same number of planetary electrons as the nearest inert gas.

These facts suggest that 2, 10, 18, 36, 54, and 86 planetary electrons (the numbers present in the inert gases) can form very stable arrangements. The stability of the planetary electrons in the inert gases is attributed to the formation of shells of electrons which are completed in these elements. The first stable shell (of two electrons) is found in helium. The third electron present in lithium commences a new shell, which is gradually added to, one electron at a time, as the Periodic Table is traversed, until it is completed (with eight electrons) in neon. With sodium a new shell begins to form, and this is completed at argon and so on.

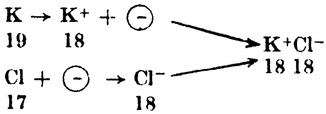
|  | Halogen Atom | Halogen Ion | Inert Gas | Alkali Metal Ion | Alkali Metal Atom |
|---|---|---|---|---|---|
| Number of planetary electrons | F = 9<br>Cl = 17<br>Br = 35<br>I = 53 | $F^-$ = 10<br>$Cl^-$ = 18<br>Br = 36<br>I = 54 | He = 2<br>Ne = 10<br>A = 18<br>Kr = 36<br>Xe = 54 | $Li^+$ = 2<br>$Na^+$ = 10<br>$K^+$ = 18<br>$Rb^+$ = 36<br>$Cs^+$ = 54 | Li = 3<br>Na = 11<br>K = 19<br>Rb = 37<br>Cs = 55 |

*Chemical combination between the elements is due to the tendency of each atom to obtain the inert gas number of planetary electrons which causes stability.*

There are three main types of combination which enable every element forming a given compound to have its appropriate inert gas number of electrons.

(*a*) *Electrovalency.* The combination of potassium and chlorine is pictured thus—

The potassium atom has nineteen electrons, one in excess of the stable inert gas number (A = 18), while the chlorine atom has seventeen electrons, i.e. one fewer than the corresponding inert gas. Combination of the two atoms occurs by the transference of an electron from potassium to chlorine, so that both atoms have the stable number of eighteen electrons. The two ions formed by the electron transfer are held together by the attraction between the opposite electrical charges.



By a similar reasoning, the positive bivalency of calcium is explained; for calcium contains two electrons more than the corresponding inert gas, so that it forms compounds by transferring two electrons.

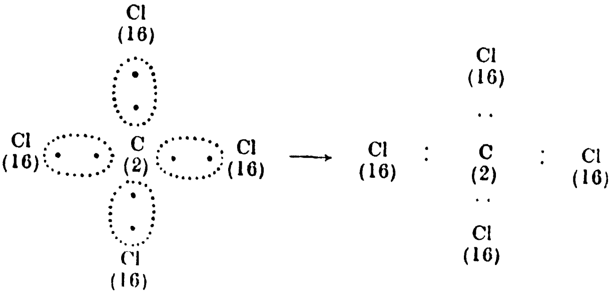
$$\underset{20}{\mathrm{Ca}} \rightarrow \underset{18}{\mathrm{Ca}^{++}} + 2\ominus$$

The compounds formed as the result of electron transfers are ionic substances such as most metallic salts. In these compounds the ions are held together by electrical attractions, which act uniformly in all directions, and not by a chemical bond occupying a definite direction in space. This type of valency is called electrovalency.

(*b*) *Co-valency*. A non-ionic linkage is characteristic of organic compounds. The bond between the atoms in this case has a definite position in space, so that the phenomena of stereochemistry (p. 419) are possible. This type of valency is known as co-valency.

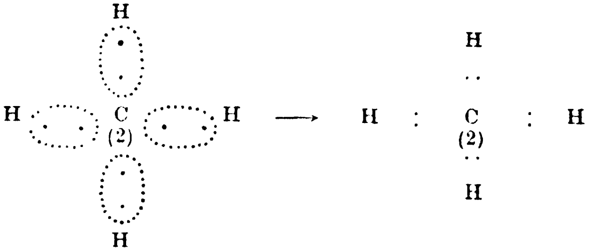
In the covalent link, the atoms acquire the electrons necessary to attain the stable inert gas electronic structure by *sharing* two electrons between two atoms. (There is no transfer of electrons from one atom to another, as in the electrovalent bond.) The process may be illustrated by considering the combination of carbon and chlorine.

Carbon is in the centre of the first short period of the Periodic Table. It is preceded by elements which achieve the inert gas structure by losing electrons and ionizing as cations, and it is followed by elements which gain electrons to achieve the inert gas structure. Carbon itself shows no tendency to form compounds either by direct giving or receiving of electrons from other atoms. Its compounds are formed by covalent linkages, so that carbon compounds are typically non-ionic, insoluble in water, and much slower in reacting than inorganic ionic substances. Two carbon atoms combine with one another by covalent linkages. The electrical neutrality of such linkages partly explains the power of carbon atoms to combine together to form chains, rings, etc., to an almost unlimited extent.



Carbon has six planetary electrons, and requires four more to achieve the inert gas structure (Ne = 10). A chlorine atom requires one more electron to achieve the inert gas structure. When carbon combines with chlorine, one electron of the carbon forms a pair with one electron from the chlorine, and these two electrons are then held in common between the two atoms. By this sharing each atom has acquired another electron, so that when combination takes place in the ratio C : 4Cl, complete stability is attained. The combination may be represented as shown on p. 309, where for convenience in writing, the electrons not directly taking part in the combination are written in brackets, and not written out in full.

Hydrogen (At. No. = 1) is an atom which can achieve stability by losing an electron and forming the hydrogen ion ($H^+$) with no planetary electrons, or by acquiring an electron and passing to the helium (He = 2) structure. In its compounds with carbon, hydrogen gains an electron, by electron-sharing with a carbon atom. The formation of methane may be represented in a manner which illustrates the observed equivalence of the carbon valencies in methane.



In the case of a co-valent bond between two similar atoms and also for bonds between carbon and hydrogen atoms, the shared electrons are equally shared, i.e. they can be regarded conventionally as placed exactly midway between the two atoms. But in other cases, the sharing is unequal, so that they can be regarded as being rather nearer one atom than the other. In such cases the system forms an electric dipole, i.e. there is a separation in space of the centre of the positive charges and the centre of the negative charges. The magnitude of the dipole is measured by the *dipole moment* which is equal to the product of the charge × distance of separation.

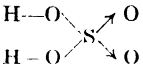
C : H
H : H

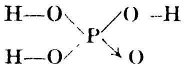
Dipole moment zero: symmetrical electron distribution.

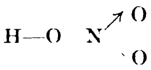
H : Cl
+ or —
H — Cl

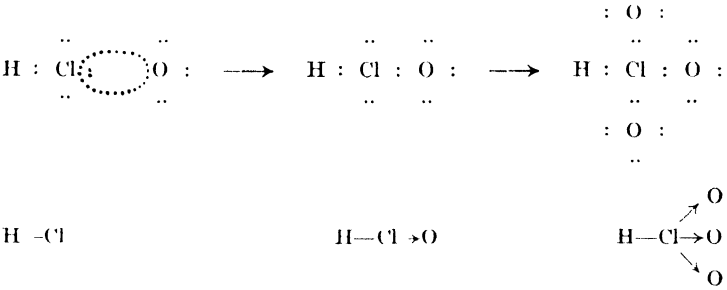
Dipole moment finite: asymmetrical electron distribution.

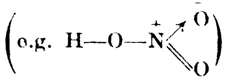
(c) *Co-ordinate Valency.* In many cases, an atom which already has an inert gas number of electrons can participate in further chemical bonds by combining with other atoms which are electron-deficient without itself losing electrons. This is achieved by sharing a pair of the satisfied atoms' electrons with the deficient atom. The bond formed (called a co-ordinate bond) resembles closely the co-valent bond and, for example, may give rise to stereoisomeric effects. To distinguish the bond symbolically it is written as an arrow pointing in the direction of the electron movement from the satisfied to the deficient atom. Many of the higher oxygen compounds are obtained through co-ordinate valencies, and also the co-ordination compounds are largely dependent on such bonds. Examples are given below, and the mechanism of the formation of the bond is illustrated by the formation of the oxy-acids of chlorine by the union of the electron satisfied chlorine atom (in HCl) with oxygen atoms each having a deficiency of two electrons. (Only the electrons actually taking part in the union are shown.)


Sulphuric acid

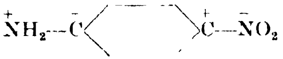

Phosphoric acid


Nitric acid

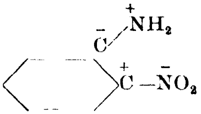


In the co-ordinate link, there is a definite movement of the electrons from the atom originally possessing them to the atom sharing them; thus the first atom acquires in bond formation a net positive charge, while the latter atom becomes negatively charged. This implies that a definite dipole is set up as a result of the link  and the dipole moments thus obtained are generally appreciably larger than those produced by asymmetry within a co-valent link.

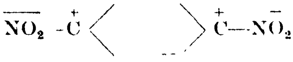
It has been possible to correlate many physical properties of substances with the net dipole moments of their molecules, the net dipole moment being obtained by summing all the individual bond moments, taking into account their directions as well as their magnitudes, e.g. in *p*. nitraniline the group dipole moments reinforce one another, in the ortho derivative they operate at an angle of 60°, while in *p.* dinitrobenzene they neutralize one another.



*p.* nitraniline



*o.* nitraniline

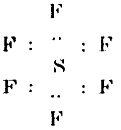


*p.* dinitrobenzene

Substances with zero dipole moment are generally of low melting and boiling point, of low solubility in water and ionizing solvents and ready solubility in organic solvents. As the dipole moment increases these physical properties change, increasing dipole moment tending to raise melting and boiling points and solubility in water and to lower solubility in organic solvents. There is also a greater tendency to form double or more complex molecules.

The above three main types of chemical bond do not exhaust the possibilities of chemical union, nor does it always follow that in the molecule of every stable chemical compound every atom possesses an inert gas number of electrons. The polymerization of the simple water molecules (p. 148) involves what are known as "hydrogen bonds" where hydrogen can by a special mechanism act as a link between two oxygen atoms (H—O—H—O—H—O—H, etc.). Examples of stable compounds where one atom does not possess an inert gas number of electrons are

nitric oxide $\cdot\overset{\cdot\cdot}{\underset{\cdot\cdot}{N}}:O$ ; sulphur hexafluoride



$$\begin{array}{ccc} & F & \\ F: & \cdot\cdot & :F \\ & S & \\ F: & \cdot\cdot & :F \\ & F & \end{array}$$

; and most salts of the transition elements where the metal exerts its ordinary relatively low valency (e.g. $Cu^{++}$, $Fe^{+++}$, $Fe^{++}$, etc.)

Some compounds can be represented with two electron arrangements but an identical atomic arrangement, e.g. A = B — A and A — B = A could be of this type. In such cases, only one chemical individual may be obtained, and this has an electronic structure intermediate between the two extremes; in the case quoted the two A atoms have equal shares in all the bond-forming electrons. The phenomenon is called *resonance* and the compound is a *resonance hybrid.* Resonance is one of the factors contributing towards the formation of a hydrogen bond.

## The Structure of Crystals

Crystals differ from gases, liquids, or glassy amorphous substances in the regular and orderly manner in which the constituent atoms are arranged. The properties of the crystal (symmetry, shape, and easy cleavage in certain directions) are due to this regular arrangement.

The arrangement of the atoms in crystals is determined by X-ray diffraction experiments. (X-rays may be compared to very short light waves. Their wave-length is of the order of size of the spacings of the atoms in crystals. Consequently, X-rays are diffracted by crystals as light is diffracted by a diffraction grating.)

*Crystals of Ionic Substances.* It has been shown that crystal structures fall into two main classes. The first class consists of crystals, such as sodium chloride, in which the constituent particles are ions. These crystals are composed of ionic aggregates, held together as compactly as possible by electrical attractions. These structures contain no definite molecules. The substances are completely ionized even in the crystalline condition. For example, in the case of sodium chloride, each sodium ion tends to be surrounded by chloride ions, and vice versa. The whole crystal is made up of an alternating arrangement of chloride and sodium ions as illustrated in the Fig. 26, where the sizes of the ions are proportionately much reduced in order to show their arrangement.

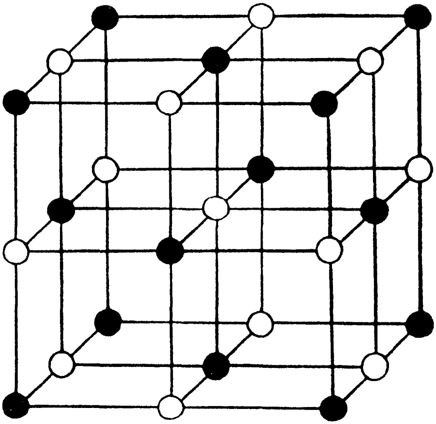


FIG. 26. CRYSTAL STRUCTURE OF SODIUM CHLORIDE

The exact arrangements of the ions in crystals of this type depend on the relative sizes and numbers of the positive and negative ions rather than their chemical nature, e.g. with caesium chloride, each caesium ion can be surrounded by eight chloride ions, but the relatively smaller sodium ion can be surrounded in sodium chloride by only six chloride ions. Thus caesium chloride and sodium chloride crystallize in different forms. Yet sodium fluoride and magnesium oxide crystallize in the same form since the ratios of the cation and anion diameters are the same in each salt.

In salts containing ions composed of more than one atom (e.g. $CaCO_3$) the ions are arranged in a manner which depends on their relative sizes and shapes. Thus, calcium carbonate and sodium nitrate ($Ca^{++}CO_3^{--}$; $Na^+NO_3^-$) exist in isomorphous forms, since the shapes of the two anions are similar and bear similar relations in respect of size to the two cations.

*Crystals of substances of the non-ionic type* cannot be made of closely packed ionic aggregates, but the atoms are linked together by separate chemical bonds. In organic substances, the molecule has a definite existence as such, and possesses a definite shape. The crystals are composed of arrangements of molecules, often quite widely separated from one another. The shape of the molecules of such substances can be deduced by the X-ray study of the crystals, e.g. benzene crystals contain flat regular hexagonal benzene molecules; methane crystals are composed of arrangements of regular tetrahedral methane molecules; and the crystals of stearic acid are composed of long chain molecules arranged parallel to one another. Many complicated molecular structures have been fully elucidated by X-ray crystal analysis (e.g. certain sterols and penicillin).

## The Electron Microscope

Under certain conditions, electrons cease to behave as single moving particles but behave instead as if they were of a wave nature, with a wave-length much shorter than light. The power of a microscope to separate objects extremely close together is limited by the length of a light wave, and by using electrons as very short light waves, smaller objects can be identified than can be seen by an ordinary microscope. X-rays could theoretically be used instead of electrons, but no way is known of focusing them by means of a system of lenses like the optical system of a microscope focusing the light rays. Owing to their electric charges, electrons can be focused using either electric or magnetic fields and the electron microscope reproduces optical lens systems in this way. The limits of resolving power of present-day instruments are as follows—

| | |
|---|---|
| Ordinary microscope limit of vision | $2 \times 10^{-5}$ cm |
| Electron microscope limit of vision | $1\cdot5 \times 10^{-7}$ cm |
| Colloid particle sizes | $10^{-7}$ to $10^{-5}$ cm |
| Virus sizes | 3 to $5 \times 10^{-6}$ cm |
| Molecular sizes | $5 \times 10^{-8}$ to $5 \times 10^{-6}$ cm |
| Atom sizes | $10^{-8}$ cm |

# SECTION IV

# ORGANIC CHEMISTRY

# CHAPTER XX

## INTRODUCTION

THE chemistry of those substances which are closely related to the metabolism of living organisms, is, in general, more complex than the chemistry of inorganic substances. In the early history of chemistry, a distinction had been made between organic and inorganic chemistry, the former being restricted to the study of the various chemical products obtainable from living sources.

A large number of these substances and many facts concerning their behaviour were discovered. It was believed that these compounds differed fundamentally from the compounds of inorganic chemistry, by the possession of some "vital principle." That this was not so was shown by Wöhler in 1828, when he obtained a very typical organic substance (urea) from an inorganic source (ammonium cyanate, cf. p. 230). From that time, although it was realized that there was no fundamental difference between the organic and inorganic compounds, the division of chemistry into two distinct branches has been retained as a matter of convenience.

As now understood, organic chemistry refers to the chemistry of carbon, which forms a very much larger number of compounds than any other element. The carbon compounds differ in many ways from the compounds of the other elements. They are typically non-ionic, and many of them are very complex, owing to the tendency of carbon atoms to combine together to an almost unlimited extent.

Almost all the organic compounds contain hydrogen in addition to carbon. Many also contain oxygen or nitrogen, and less commonly, sulphur, phosphorus, arsenic, and other elements.

# CHAPTER XXI

## THE HYDROCARBONS

THE substances formed by the union of carbon and hydrogen are called *hydrocarbons*. There is a very large number of these compounds formed by the union of the two elements in different proportions, but they fall naturally into classes. All the members of a class resemble one another in their chemical properties, and their molecular formulae are closely related. The classes may be named after their simplest member, e.g. the methane series of hydrocarbons is related to methane ($CH_4$), while the ethylene, acetylene, and benzene series are related to ethylene ($C_2H_4$), acetylene ($C_2H_2$), and benzene ($C_6H_6$) respectively.

The hydrocarbons of the methane series are also called the *paraffin* hydrocarbons, and the properties of these hydrocarbons and their derivatives occupy an important position in organic chemistry. These compounds and their derivatives, whose properties are described in the succeeding chapters, are the *aliphatic* or fatty compounds. The hydrocarbons of the benzene series and their derivatives (the *aromatic* compounds) are described later.

## THE PARAFFIN HYDROCARBONS

Methane, a hydrocarbon of the formula $CH_4$, is the simplest member of a series of hydrocarbons of which ethane ($C_2H_6$), propane ($C_3H_8$), butane ($C_4H_{10}$), and pentane ($C_5H_{12}$) are the members immediately following methane. A large number of these hydrocarbons is known of widely different complexity up to $C_{60}H_{122}$, the members after butane being named in accordance with the number of carbon atoms in their molecule (e.g. pentane $C_5H_{12}$, hexane $C_6H_{14}$, etc.).

The formulae of all these hydrocarbons can be represented by $C_nH_{2n+2}$, where $n$ is an integer; any member of the series differs from its neighbours by $CH_2$. These hydrocarbons constitute an example of a *homologous series.*

A homologous series may be defined as *a series of organic* *compounds possessing similar chemical properties, whose molecular formulae show a constant difference of* $CH_2$ *from member to member as the series is ascended.*

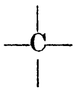
The physical properties of the members of a homologous series change steadily as the molecular weight increases. The members of a homologous series are said to be *homologues* of one another.

The existence of these series of closely related and similar substances simplifies the study of organic chemistry. It is necessary to study only the general properties and the general methods of preparation of one member as a type of each different homologous series, except in a few cases where individual differences may be important. In particular it is often found that the first member (i.e. the member with the simplest formula) of a homologous series differs to some extent from the succeeding members.

## Formulae of the Paraffin Hydrocarbons

The simple formulae (e.g. $CH_4$, $C_2H_6$, $C_3H_8$, etc.) which have been used up to the present give little indication of the arrangement of the carbon and hydrogen atoms within the hydrocarbon molecule. In order to express the structure it is necessary to indicate in the written formulae how each atom is chemically united. This can be done by the use of *graphic formulae*, where the link between each atom is signified by a stroke on the paper. By the use of these formulae the whole structure of the compound can be seen at a glance.

In organic chemistry, carbon is almost invariably quadrivalent (i.e. it unites with four univalent atoms or radicals, or two bivalent atoms or radicals, etc.). Therefore the carbon atom can be represented thus—

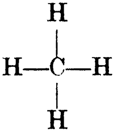


$$-\overset{|}{\underset{|}{C}}-$$

where each stroke represents one of the valencies of the carbon atom, all of which are equivalent to one another.

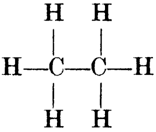
This method of writing the valencies of the carbon atom is chosen for convenience. It should not be assumed that the valencies of the carbon atom are in one plane, as here represented. A discussion of the arrangement in space of the valencies will be found later (p. 419).

In accordance with this representation of the carbon atom, the formula of methane is



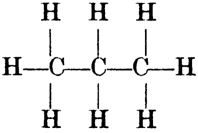
$$\begin{array}{c} H \\ | \\ H-C-H \\ | \\ H \end{array}$$

The only arrangement of the atoms in the ethane molecule ($C_2H_6$) which is consistent with the quadrivalent carbon atom and the univalent hydrogen atom is represented by the formula



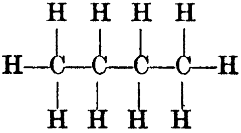
$$\begin{array}{ccccccc} & & H & & H & & \\ & & | & & | & & \\ H & - & C & - & C & - & H \\ & & | & & | & & \\ & & H & & H & & \end{array}$$

This formula (which was established experimentally, cf. reaction 2, p. 340) shows that the two carbon atoms are linked together. In propane [($C_3H_8$), the next member of the homologous series of paraffin hydrocarbons] the three carbon atoms are linked together as represented by the formula



$$\begin{array}{ccccccccc} & & H & & H & & H & & \\ & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & \\ & & H & & H & & H & & \end{array}$$

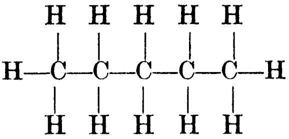
and the higher members of the series are also formed by linkage of carbon to carbon; e.g. butane ($C_4H_{10}$), and pentane ($C_5H_{12}$) can be represented by the formulae



$$\begin{array}{ccccccccccc} & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & \end{array}$$

Butane

and



$$\begin{array}{ccccccccccc} & & H & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & H & & \end{array}$$

Pentane

In this way *chains* are formed by the linkage of carbon atoms to one another.* (This unique property of the carbon atom of uniting with other carbon atoms to an almost unlimited extent has been commented upon earlier, p. 218.)

The molecule of each member of the paraffin series of hydrocarbons is built up of a chain of quadrivalent carbon atoms, the difference of $CH_2$ between one member of the series and the next being due to the presence of an additional $\begin{array}{c} H \\ | \\ -C- \\ | \\ H \end{array}$ group in the chain.

A similar relationship holds between the members of any homologous series, the molecular weight being determined by the length of the carbon chain in the molecule.

## Isomerism Among the Paraffin Hydrocarbons

In organic chemistry, a large number of cases are known where two or more different substances have exactly the same molecular formula. These substances are said to be *isomeric.* They are *isomers* of one another. The differences can be attributed to the different arrangements of the various atoms within the molecule, and there are different classes of isomerism in accordance with the various ways of obtaining different arrangements of the atoms. In the case of the paraffins, the isomerism is of the simplest type, and is often described as *branched-chain isomerism* to describe the way in which it arises.

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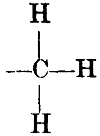
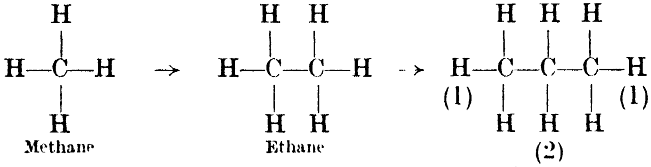
*In this method of writing these formulae, the chains are represented as straight lines. For an explanation of a truer representation, see p. 421.

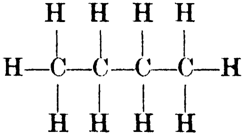
The molecular formula of one paraffin hydrocarbon can be derived from its predecessor by the substitution of  $-\overset{H}{\underset{H}{C}}-H$ for a hydrogen atom. When this is done in the molecules of methane or ethane the product has the same formula whichever hydrogen atom is chosen.



Methane Ethane Propane

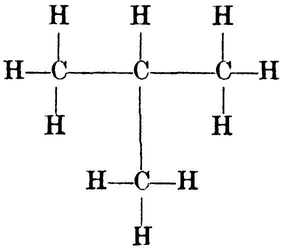
But when the propane molecule is so substituted, two products are possible, depending on whether a hydrogen atom numbered 1 or 2 is substituted.

(1)



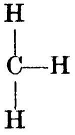
Normal butane

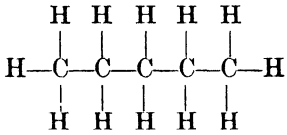
(2)



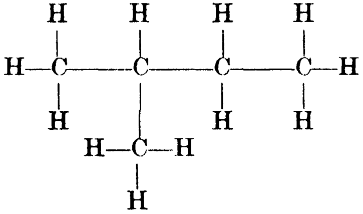
Isobutane

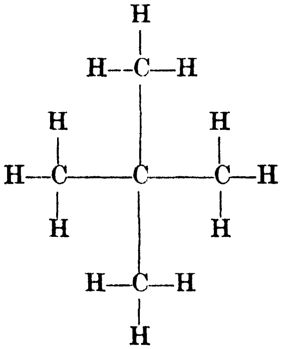
Of these two products (of formula $C_4H_{10}$), one has a straight chain of carbon atoms, the other has a formula with a branched chain. The two substances are known as *normal butane* and *isobutane.* (The term normal is reserved for substances containing straight chain molecules.)

By substitution of a  $\begin{array}{cc} H & \\ | & \\ C & -H \\ | & \\ H & \end{array}$ group for a hydrogen atom of butane or isobutane, the formulae for the $C_5H_{12}$ hydrocarbons can be derived. There are three isomeric pentanes represented by the formulae—



$$\begin{array}{ccccccccccccc} & & H & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & H & & \end{array}$$



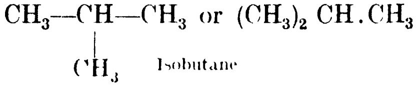


The number of possible isomers increases very rapidly as the complexity of the paraffin molecule increases.

The number of isomers predicted for the lower members of the series agrees with the number isolated experimentally. This confirms the two principles on which the prediction was based, namely (1) the quadrivalency of carbon, (2) the linkage of carbon to carbon to form chains.

The graphic formulae represented on p. 323 can be simplified by writing them as follows—

| | | | |
|---|---|---|---|
| $CH_4$ | $CH_3.CH_3$ | $CH_3.CH_2.CH_3$ | $CH_3.CH_2.CH_2.CH_3$ |
| Methane | Ethane | Propane | Butane |



$$CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{CH}}{-}CH_3 \text{ or } (CH_3)_2\,CH.CH_3$$

Isobutane

where the number of hydrogen atoms attached to a carbon atom is indicated by a suffix, and the carbon–carbon linkage is represented by a point. Formulae of this type are used frequently in organic chemistry. They show in detail the arrangement of the different atoms in the particular molecule, and are called in consequence *structural* or *constitutional formulae*.

## Occurrence and Extraction of Paraffin Hydrocarbons

Methane is present in natural gas (an inflammable gas issuing from the earth in various localities), in the gases escaping from coal in mines (fire-damp), and in the gases rising from the decomposing vegetable matter in marshes (marsh-gas). It is also an important constituent of commercial coal-gas.

A large number of paraffin hydrocarbons occur naturally in petroleum, which probably originated from the action of pressure on decomposing organic matter. American petroleums consist chiefly of a mixture of these hydrocarbons. The products obtained from other oilfields contain also hydrocarbons of other series (e.g. Russian petroleum contains large quantities of hydrocarbons of the cycloparaffin series, p. 541).

The various constituents of crude petroleum oil are partially separated by fractional distillation. The following fractions may be collected: (1) gasoline up to 80°C, (2) naphtha from 80°C to 100°C, (3) kerosene or burning oil from 150°C to 300°C, (4) lubricating oil, (5) soft paraffin wax, (6) hard paraffin wax, (7) a residue of pitch or coke which remains in the still.

The lower fractions are purified by successive treatment with sulphuric acid and dilute caustic soda solution followed by redistillation. Soft and hard paraffin wax are purified by melting and filtration through charcoal.

Soft and Hard Paraffin of the *British Pharmacopœia* melt at 38°C to 56°C, and 50°C to 57°C respectively. Liquid Paraffin is an oily liquid of density 0·865 to 0·890 g per mil at 20°C and of a certain minimum viscosity of 64 centistokes at 37·8°C. Light Liquid Paraffin weighs correspondingly 0·830 to 0·870 g per mil and has a maximum viscosity of 33·1 centistokes. Light Petroleum (petroleum ether), a very volatile, highly inflammable liquid, is obtained from the lowest boiling fractions of petroleum (e.g. b.p. 40°C to 50°C or 50°C to 60°C).

Each of these products consists of a mixture of several different members of the series of paraffin hydrocarbons.

Commercially, the lower boiling fractions are the most important. The yield of these is increased by *cracking*, where the heavier crude oils are decomposed by heating in the absence of air to a moderate temperature at high pressure in the presence of a catalyst (usually 400–500 C with pressures up to 100 atmospheres). The molecules of the higher members of the paraffin series are split up into carbon, a mixture of simpler members, and hydrocarbons of the ethylene series (e.g. $C_4H_{10} = C_2H_6 + C_2H_4$). The latter then polymerize, giving not only paraffins but also hydrocarbons of other series, such as the ethylene, cycloparaffin, and benzene series (pp. 329; 486). These hydrocarbons improve the utility of the petroleum for motor fuel, as their presence results in smoother combustion without detonation.

*Other Processes for the Extraction of Hydrocarbon Oils.* Quantities of hydrocarbon oils are obtained by the destructive distillation of certain oil-bearing shales. The oils are separated from the ammoniacal liquor fraction of the distillate, and are then redistilled, yielding similar fractions to crude natural oils.

The tar obtained from the *low temperature carbonization of coal* yields, after separation from acid and basic matter, an oil capable of being used as a motor spirit. It contains a high proportion of hydrocarbons of the ethylene series.

When coal is heated with hydrogen at a pressure of about 200 atmospheres and a temperature about 400–500°C, union between the carbon and hydrogen takes place to give hydrocarbons, gaseous, liquid and solid (*hydrogenation of coal*). By distillation of the product of the reaction, an oil suitable for use as a motor fuel is obtained. It consists mainly of ethylenic and aromatic hydrocarbons.

## General Methods of Preparation of Paraffin Hydrocarbons

A pure sample of any particular hydrocarbon might be obtained by a very careful fractionation of petroleum oil, but the separation would be so costly that it is impracticable. A pure specimen of a paraffin hydrocarbon may be obtained by one of the following reactions, which are available for the preparation of any member of the series.

(1) Reduction of the halogen derivative of the hydrocarbon (p. 340). The molecule of the halogen derivative differs from that of the hydrocarbon by the substitution of a halogen atom for a hydrogen atom, e.g. $CH_4$, $CH_3Br$. On reduction the halogen atom is replaced by hydrogen.

$$CH_3Br + H_2 = CH_4 + HBr$$

(2) Action of sodium on the halogen derivative (p. 340)

$$2CH_3Br + 2Na = 2NaBr + C_2H_6$$

This reaction gives rise to a hydrocarbon containing twice the number of carbon atoms present in the molecule of the halide. It can be adapted to prepare hydrocarbons containing an odd number of carbon atoms in the molecule, by using a mixture of two halogen derivatives.

$$CH_3Br + CH_3.CH_2Br + 2Na = CH_3.CH_2.CH_3 + 2NaBr$$

(3) Action of heat on a mixture of the sodium salt of a fatty acid and soda-lime (p. 385).

$$CH_3.COONa + NaOH = Na_2CO_3 + CH_4$$

(4) By the hydrolysis of a Grignard reagent (p. 474).
(5) By electrolysis of a salt of a fatty acid (p. 385).

In addition to these general methods of preparation available for all the members of the series, *methane* may be prepared in small quantities by the following reactions—

(1) By the direct union of carbon and hydrogen at very high temperatures.

$$C + 2H_2 = CH_4$$

(2) By reduction of carbon monoxide by hydrogen in the presence of reduced nickel as a catalyst. (Reduced nickel is very often used as a catalyst in organic chemistry for reactions involving combination with hydrogen.)

$$CO + 3H_2 = H_2O + CH_4$$

(3) By the action of water on aluminium carbide (a convenient laboratory method).

$$Al_4C_3 + 12H_2O = 4Al(OH)_3 + 3CH_4$$

(4) By passing a mixture of hydrogen sulphide and carbon disulphide over red-hot copper.

$$CS_2 + 2H_2S + 8Cu = CH_4 + 4Cu_2S$$

## Physical Properties of the Paraffin Hydrocarbons

The physical properties of the paraffin hydrocarbons vary gradually as the molecular weight increases. The *boiling point* and *melting point* rise gradually. The lowest members are gases, then follow very volatile liquids, less volatile liquids, and finally waxy solids. At the same time, the *specific gravity* increases as the number of carbon atoms in the molecule increases, although after about $C_{11}$ the difference from compound to compound becomes very small.

These variations in physical properties are similar to those shown by the members of most other homologous series. They are illustrated in the following table.

TABLE VIII

| Hydrocarbon | Formula | Melting Point | Boiling Point | Specific Gravity |
|---|---|---|---|---|
| | | (°C) | (°C) | |
| Methane | $CH_4$ | -186 | -160 | 0·415 at b.p. |
| Ethane | $C_2H_6$ | -172 | - 93 | 0·446 at 0°C |
| Propane | $C_3H_8$ | | - 45 | 0·536 at 0°C |
| Butane | $C_4H_{10}$ | — | 1 | 0·600 at 0°C |
| Isobutane* | $C_4H_{10}$ | — | - 11 | — |
| Pentane | $C_5H_{12}$ | — | 36·3 | 0·627 at 14°C |
| Hexane | $C_6H_{14}$ | | 69 | 0·658 at 20°C |
| Heptane | $C_7H_{16}$ | — | 98 | 0·683 at 20°C |
| Octane | $C_8H_{18}$ | — | 125·8 | 0·702 at 20°C |
| Nonane | $C_9H_{20}$ | -51 | 150 | 0·718 at 20°C |
| Decane | $C_{10}H_{22}$ | -31 | 173 | 0·730 at 20°C |
| Undecane | $C_{11}H_{24}$ | 26 | 195 | 0·774 at m.p. |
| Dodecane | $C_{12}H_{26}$ | -12 | 214 | 0·774 at m.p. |
| Tetradecane | $C_{14}H_{30}$ | 4 | 252 | 0·775 at m.p. |
| Hexadecane | $C_{16}H_{34}$ | 18 | 287 | 0·775 at m.p. |
| Eicosane | $C_{20}H_{42}$ | 37 | — | 0·778 at m.p. |
| Hentriacontane | $C_{31}H_{64}$ | 68 | — | 0·779 at m.p. |
| Hexacontane | $C_{60}H_{122}$ | 101 | — | 0·782 at m.p. |

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* It is a general rule that the normal isomer has a higher boiling point than any isomer with a branched chain.

The *solubilities* of the paraffin hydrocarbons resemble those of many other neutral organic substances. They are insoluble in water, but dissolve readily in, or are themselves good solvents for, many other non-ionic substances, e.g. chloroform, ether, essential oils.

## Chemical Properties of the Paraffin Hydrocarbons

The chemical properties of the paraffin hydrocarbons are characterized by neutrality towards indicators and a general chemical inertness. They do not react with ordinary reagents such as acids, alkalis, oxidizing or reducing agents. (Even fuming nitric acid only reacts slowly to oxidize them.) The name paraffin (cf. *parum affinis*) was given as an expression of this chemical inertness.

They take part in the following two reactions—

(1) They combine directly with oxygen, burning or exploding in air.

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$
$$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$$

(2) They react with chlorine and bromine, a hydrogen atom becoming replaced by an atom of the halogen. This process, by which an atom of one element is replaced by an atom of another is called *substitution*. In this case substitution is not restricted to one atom of hydrogen, but all may be replaced atom by atom in successive stages, as represented by the series of equations.

$$CH_4 + Cl_2 = \underset{\text{Methyl chloride}}{CH_3Cl} + HCl$$
$$CH_3Cl + Cl_2 = \underset{\text{Methylene dichloride}}{CH_2Cl_2} + HCl$$
$$CH_2Cl_2 + Cl_2 = \underset{\text{Chloroform}}{CHCl_3} + HCl$$
$$CHCl_3 + Cl_2 = \underset{\text{Carbon tetrachloride}}{CCl_4} + HCl$$

As a result of these substitution reactions, compounds are obtained which contain a residue of the paraffin hydrocarbon molecule, attached to one or more halogen atoms. These residues, like the original paraffin hydrocarbon molecules, are characterized by chemical inertness, and so these products of substitution react primarily through their halogen atoms. By a series of reactions these halogen atoms may be replaced by other atoms or groups of atoms to form new compounds all of which contain the groups $CH_3$, $CH_2$, etc., for example, $CH_3Cl$, $CH_3(NH_2)$, $CH_3(OH)$, etc.

A group of atoms which passes unchanged from one compound to another in this way is called a *radical.* These paraffin hydrocarbon residues are radicals which possess functions as important in organic chemistry as the metallic and acidic radicals in inorganic chemistry. They are named in accordance with the hydrocarbon from which they are derived. The most important radicals are those where only one atom of hydrogen has been displaced from the hydrocarbon molecule, and these radicals have the termination "yl." The radicals where two atoms of hydrogen have been displaced have the termination "ene."

For example—

$CH_4$ methane, $CH_3$ methyl radical, $CH_2$ methylene radical.

$C_2H_6$ ethane, $CH_3.CH_2$ or $C_2H_5$ ethyl radical, $C_2H_4$ ethylene radical.

$C_3H_8$ propane, $CH_3.CH_2.CH_2$ or $C_3H_7$ propyl radical, $C_3H_6$ propylene radical, etc.

The term *alkyl* radical is used as a general term to represent any of the radicals methyl, ethyl, propyl, butyl, etc. In naming compounds containing these radicals, the radical is usually stated first, e.g. methyl chloride $CH_3Cl$, ethyl bromide $C_2H_5Br$, or generally, alkyl halide. The radicals are sometimes written Me = methyl, Et = ethyl, Alk = alkyl, etc.

## HYDROCARBONS OF THE ETHYLENE SERIES

The gas ethylene is the simplest member of a homologous series represented by the general formula $C_nH_{2n}$. The ethylene hydrocarbons differ from the corresponding members of the paraffin series in having two atoms of hydrogen less in their molecules. Their names are derived from the corresponding paraffin by replacing the terminal "-ane" by "-ylene," e.g. ethylene, propylene, butylene.

### Preparation of Ethylene and its Homologues

(1) The destructive distillation of wood, coal, or the higher fractions of petroleum oil (cracking) gives rise to considerable

quantities of ethylenic hydrocarbons. Some of these are important industrially (e.g. propylene) as sources from which more complex compounds are derived. (The illuminating power of coal-gas is partly dependent on its ethylene content.)

(2) In the laboratory, ethylene hydrocarbons are prepared by the removal of water from alcohols (see p. 351). This is usually carried out by heating with a dehydrating agent, commonly sulphuric acid.

$$C_2H_5OH = C_2H_4 + H_2O$$

(3) Ethylene hydrocarbons are also prepared on a small scale by removal of a molecule of hydrogen halide from the molecule of a halogen derivative of a paraffin hydrocarbon. This is usually carried out by treatment with concentrated alcoholic potash. The simplest reaction of this type, represented by the equation below is less effective than with similar but more complex compounds (cf. preparations of chlorinated ethylenes, p. 347).

$$C_2H_5I + KOH = KI + H_2O + C_2H_4$$

(4) The addition of hydrogen to acetylene derivatives may form the corresponding ethylene compound.

(5) Ethylene hydrocarbons are also obtained by electrolysis of the salts of dibasic acids (cf. p 385).

## Physical Properties of the Ethylenic Hydrocarbons

These vary in a similar manner to those of the paraffin hydrocarbons. Ethylene itself is slightly soluble in water, but the higher members are insoluble.

## Chemical Properties of the Ethylenic Hydrocarbons

Chemically the ethylenic hydrocarbons are very different from the paraffin hydrocarbons. They are reactive, and enter into the following reactions—

(1) They combine rapidly with the halogens, compounds being formed by addition of one molecule of the halogen to one molecule of the ethylenic hydrocarbon.

$$\underset{\text{Ethylene}}{C_2H_4} + Br_2 = \underset{\substack{\text{Ethylene}\\\text{dibromide}}}{C_2H_4Br_2}$$

When a substance reacts by adding on molecules or groups without displacement of other groups, *addition* is said to take place, and the substance formed is described as an *addition product*.

The contrast between the *substitution* reactions of the paraffins and the *addition* reactions of the ethylenes, is shown in the equations—

$$\underset{\text{Methane}}{CH_4} + Cl_2 = \underset{\text{Methyl chloride}}{CH_3Cl} + HCl \quad \text{(substitution)}$$

$$\underset{\text{Ethylene}}{C_2H_4} + Br_2 = \underset{\substack{\text{Ethylene}\\\text{dibromide}}}{C_2H_4Br_2} \quad \text{(addition)}$$

The addition products of the ethylenes are di-halogen substituted derivatives of the corresponding paraffin hydrocarbon.

(2) They form addition products with hydrogen bromide and hydrogen iodide. (The product is a halogen substitution derivative of a paraffin hydrocarbon.)

$$C_2H_4 + HI = C_2H_5I$$

(3) They add on hydrogen and form the corresponding paraffin.

$$C_2H_4 + H_2 = C_2H_6$$

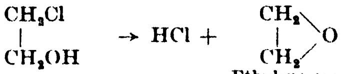
This reduction of ethylenic derivatives is carried out by bringing them, in the vapour or liquid state, into contact with hydrogen in the presence of finely divided nickel as a catalyst.

In view of the ease with which ethylene and its homologues add on halogens, halogen hydrides, and hydrogen, they are said to be *unsaturated*. The paraffin hydrocarbons which react only by replacement of their hydrogen (and do not form derivatives by addition) are said to be *saturated*.

(4) Ethylenic hydrocarbons add on hypochlorous or hypobromous acid when passed into aqueous solutions of chlorine or bromine. The products are called chloro- or bromo-hydrins.

$$CH_2 = CH_2 + HOCl = \underset{\text{Ethylene chlorohydrin}}{CH_2OH.CH_2Cl}$$

The chlorohydrins are converted by alkalis into ethylene oxides. Ethylene chlorohydrin in this way yields ethylene oxide itself.



$$\begin{matrix} CH_2Cl \\ | \\ CH_2OH \end{matrix} \rightarrow HCl + \begin{matrix} CH_2 \\ | \\ CH_2 \end{matrix}\!\!>\!O$$

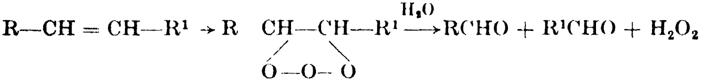
Ethylene oxide

(5) Ethylenic compounds are easily oxidized and are readily absorbed in concentrated potassium permanganate solution. The first stage of the reaction is the addition of an oxygen atom.

(6) Ethylenic compounds are absorbed by concentrated or fuming sulphuric acid and form addition compounds.

$$C_2H_4 + H_2SO_4 = \underset{\text{Ethyl hydrogen sulphate}}{C_2H_5HSO_4}$$

(7) Ethylenic compounds react readily with ozone, forming an addition compound called an ozonide, which is readily hydrolyzed, forming two carbonyl compounds (p. 353). Ozone is an important reagent for the determination of the position of a double bond in an unsaturated compound from a study of the hydrolysis products.

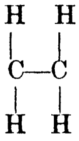


$$R—CH = CH—R^1 \rightarrow R\ \underset{O—O—O}{CH—CH}—R^1 \xrightarrow{H_2O} RCHO + R^1CHO + H_2O_2$$

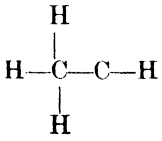
(8) Ethylenic compounds may undergo polymerization reactions (see p. 336) which have important applications in certain aspects of the manufacture of "plastics" raw materials.

## The Formula of Ethylene

There are two possible arrangements of the atoms in the molecule of ethylene, viz.—



(*a*)



(*b*)

and it is possible to deduce from the experimental behaviour of the gas that the correct formula is the symmetrical one (*a*).

The products obtained by the addition of bromine to ethylene would be

$$CH_2Br.CH_2Br \text{ or } CH_3.CHBr_2$$

depending on which formula represented the gas. On hydrolysis of these substances (by a reaction given on p. 341) the products would be $CH_2OH.CH_2OH$ (glycol) or $CH_3.CHO$ (acetaldehyde).

$$CH_2Br.CH_2Br + 2KOH = CH_2OH.CH_2OH + 2KBr$$

$$CH_3.CHBr_2 + 2KOH = CH_3.CH(OH)_2 + 2KBr$$

$$CH_3.CH(OH)_2 = CH_3.CHO + H_2O$$

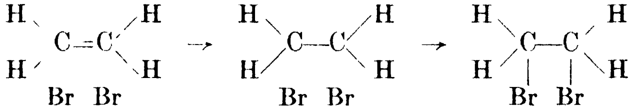
The substance formed from ethylene dibromide is glycol, and hence ethylene must be represented by the symmetrical formula.

The quadrivalency of carbon in organic compounds can be satisfied by writing the formula of ethylene thus,

$$CH_2{=}CH_2$$

the carbon atoms being united together by two valency bonds instead of one as in the paraffin hydrocarbons. Ethylene and its homologues possess a *double bond* in their molecule, and the characteristic properties of these substances must be attributed to the presence of the double bond. Substances containing carbon atoms united by double bonds react similarly to ethylene; unsaturation is a characteristic property of a double bond.

It might ordinarily be supposed that a double linkage between two carbon atoms would cause a strong binding, but the reactions of ethylenic compounds show that this is not the case. The double bond is a weak bond, and readily becomes converted by addition reactions into single bonds. This is represented in the equation



In complex substances the double bond is often the weakest point of the molecule, and the first point of chemical attack. This characteristic is often applied in the investigation of the molecular structure of unknown substances.

## Ethylene B.P.

This is obtained commercially from the products of "cracking" petroleum oils. Its purity is controlled officially by passing the gas through barium hydroxide solution (test for carbon dioxide), ammoniacal silver nitrate (test for hydrogen sulphide, phosphine, acetylene, and reducing impurities which form precipitates of silver sulphide, silver phosphide, silver acetylide, and silver respectively), and a methyl red indicator solution (test for acid impurities). The test for carbon monoxide depends on the reaction with the haemoglobin of blood.

The assay of Ethylene depends on its absorption by concentrated sulphuric acid or bromine water. A known volume of the gas is shaken with one of these reagents. The volume of the unabsorbed gas, after treatment with caustic potash to remove acids and bromine, is measured. Oxygen is removed by treatment with alkaline pyrogallol solution. The residual gas should contain no carbon monoxide as indicated by the absence of a contraction when shaken with acid cuprous chloride solution.

## HYDROCARBONS OF THE ACETYLENE SERIES

The members of this series of hydrocarbons have the general formula $C_nH_{2n-2}$; they possess two atoms of hydrogen less than the corresponding member of the ethylene series, and four atoms less than the corresponding paraffin hydrocarbon. As the ethylenic hydrocarbons possess a double bond in the molecule, so the formula of the acetylenic compounds are represented with a *triple bond.* (For example the formula of acetylene itself is $CH \equiv CH$.)

The next member of the series is called allylene ($CH_3.C\equiv CH$), while higher members are usually regarded as derivatives of acetylene and are named as such, e.g. ethylacetylene ($C_2H_5.C\equiv CH$).

### Preparation of Acetylene

(1) Acetylene is obtained when other hydrocarbons are heated to a very high temperature, e.g. by passing methane or ethylene through an electric arc.

$$2CH_4 = C_2H_2 + 3H_2$$
$$C_2H_4 = C_2H_2 + H_2$$

Acetylene is also formed in small quantities when hydrogen is passed through an electric arc between carbon electrodes.

$$2C + H_2 = C_2H_2$$

(2) Acetylene is prepared on a large scale by the action of water on calcium carbide.

$$CaC_2 + 2H_2O = Ca(OH)_2 + C_2H_2$$

It is marketed in cylinders in the form of a solution in acetone. It is used for acetylene welding purposes, and for conversion into other important organic compounds (p. 377).

(3) Acetylene and its homologues can be prepared from the

addition product obtained by the union of an ethylenic hydrocarbon with a halogen. By reacting with alcoholic potash two molecules of hydrogen halide are removed.

$$C_2H_4 + Br_2 = C_2H_4Br_2$$
$$C_2H_4Br_2 + 2KOH = 2KBr + 2H_2O + C_2H_2$$

## Properties of the Acetylenic Hydrocarbons

The variations in the *physical properties* of the homologues of acetylene are similar to those of the other series of hydrocarbons.

The *chemical properties* are characterized by great reactivity. The double bond of ethylenic compounds is reactive, and shows a tendency to become converted into the single bonds of saturated compounds. The triple bond of the acetylenic hydrocarbons is even more reactive, and is readily converted either into a double bond or into a single bond as illustrated by the following reactions.

(1) Acetylene adds on halogens very readily. The reaction takes place in two stages, first one molecule being added, giving a double-bonded compound, which then adds on another molecule giving a completely saturated compound.

$$\underset{\text{Acetylene}}{CH \quad CH} + Br_2 = \underset{\text{Dibromoethylene}}{CHBr{=}CHBr}$$
$$\underset{\text{Dibromoethylene}}{CHBr{=}CHBr} + Br_2 = \underset{\text{Tetrabromoethane}}{CHBr_2.CHBr_2}$$

(2) Acetylenes add on hydrogen halides in two corresponding stages.

$$CH \quad CH + HBr = \underset{\text{Vinyl bromide}}{CH_2{=}CHBr}$$
$$CH_2{=}CHBr + HBr = \underset{\text{Ethylidene dibromide}}{CH_3.CHBr_2}$$

The products formed by the addition to acetylene of halogens and halogen acids are manufactured for use as solvents.

(3) When treated with hydrogen in the presence of a catalyst, acetylenic compounds are converted first into ethylenic and then into saturated compounds.

$$C_2H_2 + H_2 = C_2H_4$$
$$C_2H_4 + H_2 = C_2H_6$$

(4) In the presence of sulphuric acid and a catalyst, acetylene combines with water (p. 377).

$$C_2H_2 + H_2O = CH_3.CHO$$

(5) Acetylene hydrocarbons *polymerize* on heating, e.g. acetylene passed through a red-hot tube forms benzene (p. 489).

$$3C_2H_2 = C_6H_6$$

*Polymerization* occurs when several molecules of a substance combine to form a single molecule of a substance of higher molecular weight, but containing the same elements united in the same proportion.

(6) Under certain circumstances the hydrogen of acetylene and its homologues of the type $CH{\equiv}CR$ is replaceable by a metal. If acetylene is passed into an ammoniacal solution of cuprous chloride, a deposit of copper acetylide is obtained. Similarly, silver acetylide is obtained from an ammoniacal silver nitrate solution.

$$Cu_2Cl_2 + C_2H_2 + 2NH_4OH = Cu_2C_2 + 2NH_4Cl + 2H_2O$$
$$2AgNO_3 + C_2H_2 + 2NH_4OH = Ag_2C_2 + 2NH_4NO_3 + 2H_2O$$

The metallic derivatives are unstable and liable to violent explosion. When treated with dilute acids they decompose, regenerating the hydrocarbon, and can therefore be used as a means of separation and purification of these acetylene hydrocarbons. The hydrogen atoms of paraffins or ethylenes are not replaceable by metals.

## CHAPTER XXII

# DERIVATIVES OF THE HYDROCARBONS
## HALIDES: ALCOHOLS: ETHERS

## HALOGEN DERIVATIVES*

THE halogen derivatives of the paraffin hydrocarbons are derived from paraffin hydrocarbons by replacement of hydrogen by halogens. The mono-halogen derivatives (the alkyl halides) form a homologous series, and resemble one another closely in their chemical reactions.

There is a greater possibility of isomerism among the alkyl halides than among the corresponding hydrocarbons. For example, although propane exists in one form only

$$\overset{}{CH_3}.\overset{(a)}{CH_2}.\overset{(b)}{CH_3}$$

two propyl chlorides can be obtained by the replacement of a hydrogen atom, either of the central carbon atom (*a*), or of the terminal carbon atom (*b*).

$$CH_3.CHCl.CH_3 \qquad CH_3.CH_2.CH_2Cl$$

Amongst di-halogen and higher derivatives the number of isomers is even greater than with the monoderivatives, e.g. although there is only one substance having the formula $C_2H_5Cl$, there are two substances having the formula $C_2H_4Cl_2$, viz.

$$\underset{\text{Ethylidene dichloride}}{CH_3.CHCl_2} \quad \text{and} \quad \underset{\text{Ethylene dichloride}}{CH_2Cl.CH_2Cl}$$

This type of isomerism can be described as *position isomerism,* as it is conditioned by the position at which the halogen atom is introduced into the hydrocarbon molecule.

### General Methods of Preparation of Halogen Derivatives

(1) Halogen derivatives may be prepared by direct substitution of the saturated hydrocarbon by reaction with chlorine

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* Throughout this and the following sections, the term "halogen" refers only to chlorine, bromine, and iodine and not to fluorine.

or bromine. The reaction is facilitated by the presence of a catalyst (e.g. iodine) and it also proceeds more rapidly in presence of bright light.

By prolonged reaction, the hydrogen atoms may be replaced successively. For example, from methane it is possible to prepare methyl chloride, methylene dichloride, chloroform, and carbon tetrachloride in successive stages. In practice, this reaction leads to the formation of a mixture of the derivatives.

$$CH_4 + Cl_2 = HCl + CH_3Cl \text{ (methyl chloride)}$$
$$CH_3Cl + Cl_2 = HCl + CH_2Cl_2 \text{ (methylene dichloride)}$$
$$CH_2Cl_2 + Cl_2 = HCl + CHCl_3 \text{ (chloroform)}$$
$$CHCl_3 + Cl_2 = HCl + CCl_4 \text{ (carbon tetrachloride)}$$

Iodine derivatives cannot be prepared by direct substitution of a paraffin hydrocarbon.

(2) Halogen derivatives are prepared by the addition of halogens or hydrogen halides to ethylenic or acetylenic hydrocarbons.

$$C_2H_2 + 2Cl_2 = C_2H_2Cl_4 \text{ (tetrachloro-ethane)}$$
$$C_2H_4 + HI = C_2H_5I \text{ (ethyl iodide)}$$

(3) The halogen derivatives are conveniently prepared in the laboratory from the corresponding hydroxyl derivative (the alcohol), by replacement of the hydroxyl group by the halogen atom (p. 349).

The replacement may be carried out by reacting either with the halogen acid or with a phosphorus halide. A mixture of red phosphorus and the halogen is usually used for the preparation of alkyl bromides and iodides.

$$C_2H_5OH + HBr = C_2H_5Br + H_2O$$
$$3C_2H_5OH + PI_3 = 3C_2H_5I + H_3PO_3$$

(4) Certain di-halogen derivatives can be prepared from the corresponding aldehyde or ketone (p. 371).

## Physical Properties of the Halogen Derivatives of the Paraffin Hydrocarbons

The physical properties show the usual variations. Melting and boiling points rise as the number of carbon atoms in the

## TABLE IX

| Substance | Formula | Boiling Point (°C) | Specific Gravity | Substance | Formula | Boiling Point (°C) | Specific Gravity | Substance | Formula | Boiling Point (°C) | Specific Gravity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Monosubstitution Derivatives* | | | | | | | | | | | |
| **Methyl chloride**<br>**Ethyl chloride**<br>***n*Propyl chloride** | $CH_3Cl$<br>$C_2H_5Cl$<br>$C_3H_7Cl$ | 23.7<br>12.5<br>46.5 | 0.952<br>0.918<br>0.912 | Methyl bromide<br>Ethyl bromide<br>*n*Propyl bromide | $CH_3Br$<br>$C_2H_5Br$<br>$C_3H_7Br$ | 4.5<br>38.4<br>71 | 1.732<br>1.468<br>1.340 | Methyl iodide<br>Ethyl iodide<br>*n*Propyl iodide | $CH_3I$<br>$C_2H_5I$<br>$C_3H_7I$ | 45<br>72.3<br>102.5 | 2.293<br>1.944<br>1.786 |
| *Disubstitution Derivatives* | | | | | | | | | | | |
| **Methylene dichloride** | $CH_2Cl_2$ | 42 | 1.337 | Methylene dibromide | $CH_2Br_2$ | 97 | 2.948 | Methylene di iodide | $CH_2I_2$ | 180 | 3.292 |
| *Trisubstitution Derivatives* | | | | | | | | | | | |
| **Chloroform** | $CHCl_3$ | 61 | 1.490 | Bromoform | $CHBr_3$ | 151 | 2.902 | Iodoform | $CHI_3$ | Solid m p 121 | — |
| *Tetrasubstitution Derivatives* | | | | | | | | | | | |
| **Carbon tetrachloride** | $CCl_4$ | 77 | 1.604 | Carbon tetrabromide | $CBr_4$ | Solid m p 92 | — | | | | |

molecule increases. The melting and boiling points of the halogen derivatives are higher than those of the corresponding hydrocarbon, those of the iodine derivatives being the highest.

The specific gravities are greater than those of the corresponding hydrocarbons in the order iodide > bromide > chloride, but decrease gradually as the number of carbon atoms in the molecule increases. Di-halogen and higher derivatives have higher melting and boiling points and specific gravities than the corresponding mono derivatives (Table IX).

The halogen derivatives are insoluble in water, but dissolve readily in organic solvents.

## Chemical Properties of the Halogen Derivatives of the Paraffin Hydrocarbons

The aliphatic halides differ completely from the metallic halides in their reactions. In aqueous or alcoholic solution a metallic halide will precipitate silver chloride quantitatively and instantaneously. Some of these organic halides precipitate silver chloride *slowly* from an alcoholic solution (cf. p. 346), but others do not react at all. The linkage of halogen to metal is ionic, and the reaction to form the precipitate takes place between the silver and halogen *ions*. The linkage of halogen to carbon is co-valent and non-ionic, and reactions take place between *molecules* of the two compounds.

The reactions which follow result in the exchange of the halogen atom for other radicals, which become united to carbon by non-ionic linkages, as for example in the reaction

$$C_2H_5I + KOH = C_2H_5OH + KI$$

The ease of reaction is usually greatest with the iodide.

(1) The halogen derivative may be reduced to the hydrocarbon.

$$C_2H_5I + H_2 = HI + C_2H_6$$

The following reducing agents may be used to effect this conversion: concentrated hydriodic acid, or the hydrogen liberated from sodium amalgam and water or from a zinc-copper couple (zinc coated with a thin layer of copper) and water or alcohol.

(2) When alkyl halides are heated with metallic sodium,

the sodium combines with the halogen atom, and a *free radical* is formed.

$$CH_3I + Na = NaI + \ldots CH_3$$

This free radical, having an unsaturated valency, immediately combines with a similar radical, and so a molecule of a hydrocarbon, containing twice as many carbon atoms as the original halide, is formed.

$$CH_3 \ldots + \ldots CH_3 = C_2H_6$$

The complete reaction is represented by the equation

$$2CH_3I + 2Na = 2NaI + C_2H_6$$

If a mixture of two different halides is heated with metallic sodium, two unlike free radicals are formed, and react together to give a molecule of a hydrocarbon.

$$CH_3I + C_2H_5I + 2Na = 2NaI + \underset{\text{Propane}}{C_3H_8}$$

This reaction is often called the *Wurtz'* reaction, after its discoverer.

(3) The halogen atom may be replaced by the hydroxyl group. When an alkyl halide is treated with an *aqueous* solution of potassium hydroxide (or moist silver oxide which reacts as silver hydroxide), interchange takes place between the two molecules as represented in the equation

$$C_2H_5Br + KOH = C_2H_5OH + KBr$$

The substances formed by these reactions are called alcohols.

(4) Many alkyl halides react quite differently with an *alcoholic* solution of potassium hydroxide, for under these conditions a molecule of halogen acid may be removed from the alkyl halide molecule and an unsaturated compound produced.

$$C_2H_5Br + KOH = \underset{\text{Ethylene}}{C_2H_4} + KBr + H_2O$$

This reaction can be used for the preparation of unsaturated compounds containing a double bond. By removing two molecules of halogen acid from a dihalogen derivative, triple bonded acetylenic compounds may be prepared.

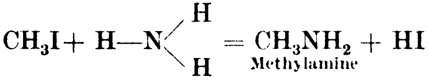
$$C_2H_4Br_2 + 2KOH = C_2H_2 + 2KBr + 2H_2O$$

Chloroform, iodoform, and carbon tetrachloride are exceptional as they behave similarly with alcoholic and aqueous potash.

$$CHCl_3 + 4KOH = 3KCl + HCOOK + 2H_2O$$

(5) The alkyl halides react with ammonia. The substances formed by the reaction are derivatives of ammonia in which the hydrogen atoms have been replaced by alkyl groups. They are called *amines*, and are classified into primary, secondary, or tertiary amines according as one, two, or three hydrogen atoms have been replaced.

When an alkyl halide is heated in a sealed tube with an aqueous or an alcoholic solution of ammonia, the first reaction results in the replacement of one atom of hydrogen by an alkyl radical, and a primary amine is obtained.



$$CH_3I + H{-}N\begin{matrix} H \\ H \end{matrix} = \underset{\text{Methylamine}}{CH_3NH_2} + HI$$

This product may then react with another molecule of the alkyl halide to form a secondary amine, and this in turn may react to give a tertiary amine.

$$CH_3NH_2 + CH_3I = \underset{\text{Dimethylamine}}{(CH_3)_2NH} + HI$$

$$(CH_3)_2NH + CH_3I = \underset{\text{Trimethylamine}}{(CH_3)_3N} + HI$$

Finally, a quaternary derivative may be formed (corresponding to an ammonium salt with the four hydrogen atoms replaced by alkyl groups).

$$CH_3I + (CH_3)_3N = \underset{\substack{\text{Tetramethylammonium} \\ \text{iodide (compare } NH_4I\text{)}}}{(CH_3)_4NI}$$

(6) The halogen atom of an alkyl halide may be replaced by the cyanide radical by reaction with potassium cyanide.

$$CH_3I + KCN = \underset{\text{Methyl cyanide}}{CH_3CN} + KI$$

This reaction is important as the cyanides may be converted into the organic acids (p. 435).

(7) Alkyl halides react with the sodium derivatives of alcohols to form ethers (p. 365).

$$C_2H_5I + C_2H_5ONa = NaI + \underset{\text{Diethyl ether}}{(C_2H_5)_2O}$$

(8) The halogen derivatives are less inflammable than the corresponding hydrocarbons.

(9) The halogen atom may be replaced by a nitro group by reacting with silver nitrite (p. 434).

$$CH_3I + AgNO_2 = \underset{\text{Nitromethane}}{CH_3NO_2} + AgI$$

(10) Silver salts of organic acids react with alkyl halides forming esters (p. 394).

$$CH_3.COOAg + C_2H_5I = AgI + \underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5}$$

(11) The alkyl halides in dry ethereal solution react with metallic magnesium to form a *Grignard reagent* (p. 474).

$$C_2H_5I + Mg \quad \underset{\substack{\text{Magnesium ethyl}\\ \text{iodide}}}{C_2H_5MgI}$$

(12) Alkyl halides react with the sodium derivatives of ethylaceto-acetate and ethyl malonate (pp. 472, 473).

## Ethyl Chloride

Ethyl Chloride ($C_2H_5Cl$) is prepared by the action of hydrogen chloride gas on ethyl alcohol, or on industrial methylated spirit (in this case a little methyl chloride is also formed). Anhydrous zinc chloride may be added as a dehydrating agent to assist the reaction by removal of the water formed (cf. p. 350).

$$C_2H_5OH + HCl = C_2H_5Cl + H_2O$$

The boiling point of methyl chloride is −23·7°C and of ethyl chloride 12·5°C, so that both substances are gaseous at ordinary pressures and temperatures. They can be liquefied by compression, and are normally distributed in sealed tubes in the liquid state.

The impurities most likely to arise from the above method of manufacture of Ethyl Chloride B.P. are hydrochloric acid and alcohol. Tests for these substances are made after they have been extracted in water. The official method of assay is an alkaline hydrolysis similar to that adopted for esters (p. 400).

## Chloroform

Chloroform ($CHCl_3$) is not conveniently prepared by the general methods for the aliphatic halides. It is usually prepared by the action of chlorine on ethyl alcohol or acetone in alkaline solution. The reactions take place in stages.

(*a*) *Ethyl alcohol* is first oxidized to acetaldehyde (p. 353).

$$\underset{\text{Ethyl alcohol}}{C_2H_5OH} + O = \underset{\text{Acetaldehyde}}{CH_3.CHO} + H_2O$$

The acetaldehyde is then substituted by chlorine to form chloral (p. 377).

$$CH_3.CHO + 3Cl_2 = \underset{\text{Chloral}}{CCl_3.CHO} + 3HCl$$

The chloral is then hydrolyzed by the alkali to form chloroform (p. 378).

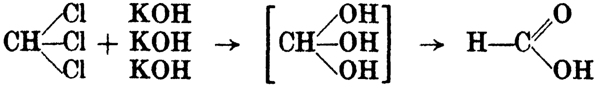
$$\underset{\text{Chloral}}{CCl_3.CHO} + NaOH = \underset{\text{Chloroform}}{CHCl_3} + \underset{\text{Sodium formate}}{HCOONa}$$

(*b*) *Acetone* is substituted by chlorine to form trichloracetone which is hydrolyzed to chloroform by the alkali.

$$CH_3.CO.CH_3 + 3Cl_2 = CH_3.CO.CCl_3 + 3HCl$$
$$CH_3.CO.CCl_3 + NaOH = CHCl_3 + CH_3.COONa$$

In the laboratory and in the manufacturing process chlorinated lime is used as a source of chlorine and alkali, the chloroform being distilled from the mixture of alcohol (or acetone) and chlorinated lime. As methyl alcohol does not give chloroform with chlorine and alkali, industrial methylated spirit can be used in the manufacturing process.

Chloroform is a heavy liquid with a characteristic odour. It is only slightly soluble in water, and is a good solvent for many organic substances. With alcoholic potash it is hydrolyzed, and potassium formate is obtained.



Formic acid (HCOOH)

Chloroform reacts with primary amines in alcoholic alkaline solution to form the characteristically evil smelling isocyanides (p. 436).

### THE CONTROL OF PURITY OF CHLOROFORM

Chloroform is rather unstable, and decomposes under the influence of light and air. Amongst the products of decomposition are chlorine, hydrochloric acid, and carbonyl chloride ($COCl_2$) the latter substance in particular being very poisonous.

$$CHCl_3 + O = HCl + COCl_2$$

The decomposition may be prevented by storage in the dark, and by the addition of alcohol. (The official substance contains 1 to 2 per cent of ethyl alcohol added for this purpose.) The mechanism of the preservative action of alcohol is not certain. It has been suggested that it is due to the removal of the first traces of the decomposition products by combination with the alcohol.

$$COCl_2 + 2C_2H_5OH = 2HCl + \underset{\text{Ethyl carbonate}}{CO(OC_2H_5)_2}$$

These decomposition products are catalysts which accelerate the decomposition, which would therefore proceed at an ever-increasing rate if the decomposition products were not removed.

Stringent tests for the presence of impurities and decomposition products are officially applied to Chloroform, owing to its use as an anaesthetic. Decomposition products are revealed by tests for acidity (with litmus) and ionizable chlorides after shaking with water.

$$COCl_2 + H_2O = 2HCl + CO_2$$

A further test for decomposition products is made by shaking the Chloroform with concentrated sulphuric acid and a little formaldehyde, when the acid layer should become only slightly discoloured.

Free chlorine, aldehyde, and organic chlorinated compounds may be present in Chloroform from the manufacturing process. Free chlorine is tested for by shaking with water and adding cadmium iodide solution and starch mucilage. The test for aldehyde depends on the formation of a yellow or brown substance with Nessler's solution (p. 281), while the chlorinated compounds are detected by silver nitrate after they have been decomposed by shaking with concentrated sulphuric acid.

## Iodoform

Iodoform ($CHI_3$) is prepared by the action of iodine on ethyl alcohol or acetone in alkaline solution. The reaction proceeds in stages as in the preparation of chloroform. On a manufacturing scale a solution of potassium iodide containing alcohol or acetone and sodium carbonate is electrolyzed. The alkali and iodine formed by the electrolysis react with the alcohol or acetone.

The official assay of Iodoform depends on its slow reaction with excess silver nitrate in aqueous-alcoholic solution. The excess silver nitrate is determined by ammonium thiocyanate titration, after removing any nitrite, formed by reduction, with urea to prevent interaction with the ferric solution used as the indicator.

$$CHI_3 + 3AgNO_3 + 2H_2O = 3AgI + HCOOH + 3HNO_3$$

The official impurity tests include one for water soluble iodides and another for added water soluble yellow colouring matter.

## Carbon Tetrachloride

Carbon tetrachloride ($CCl_4$) is prepared commercially by the action of chlorine on carbon disulphide in the presence of a catalyst (e.g. antimony).

$$CS_2 + 2Cl_2 = CCl_4 + 2S$$

It is non-inflammable (many fire extinguishers contain this substance) and not very reactive. With alcoholic caustic potash it is hydrolyzed to form potassium carbonate.

$$CCl_4 + 6KOH = K_2CO_3 + 4KCl + 3H_2O$$

Carbon Tetrachloride is not hydrolyzed by water at ordinary temperatures, so that acid or ionizable chloride impurities are officially detected by shaking with water, separating, and testing the aqueous layer with bromocresol purple or silver nitrate. Carbon disulphide and free chlorine impurities are detected by reacting with potassium plumbite (p. 266), and cadmium iodide (p. 278) respectively. Oxidizable impurities are controlled by adding potassium dichromate solution. After reacting, the excess dichromate is determined by adding potassium iodide and titrating the liberated iodine with standard sodium thiosulphate solution (cf. p. 285).

## The Halogen Derivatives of the Ethylenic Hydrocarbons

These are ethylenic hydrocarbons with hydrogen substituted by halogen, and thus contain double bonds in their molecules. They are more reactive than the corresponding paraffin hydrocarbon derivatives, e.g. they decolorize bromine as the result of addition at the double bond and some are slowly decomposed by moisture when exposed to light.

*Trichloro-ethylene* is prepared from acetylene by the addition of chlorine followed by the removal of hydrogen chloride. Dry calcium hydroxide may be used for the last reaction instead of alcoholic potash.

$$C_2H_2 + 2Cl_2 = \underset{\text{Tetrachloro-ethane}}{C_2H_2Cl_4}$$

$$C_2H_2Cl_4 \rightarrow \underset{\text{Trichloro-ethylene}}{CHCl{=}CCl_2} + HCl$$

*Tetrachloro-ethylene* is obtained from trichloro-ethylene by addition of chlorine followed by removal of hydrogen chloride with milk of lime.

$$CHCl{=}CCl_2 + Cl_2 \rightarrow \underset{\text{Pentachloro-ethane}}{CHCl_2.CCl_3}$$

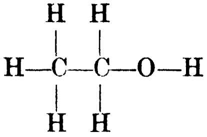
$$CHCl_2.CCl_3 \rightarrow \underset{\text{Tetrachloro-ethylene}}{CCl_2{=}CCl_2} + HCl$$

## THE ALIPHATIC ALCOHOLS

The alcohols are compounds which contain a hydroxyl group united to a paraffin hydrocarbon residue. The monohydric alcohols possess one such group in the molecule, while di-, tri-, etc., hydric alcohols possess two, three, or more hydroxyl groups. The simple mono-hydric alcohols in which the hydroxyl group is attached to an alkyl radicle form a homologous series.

## Constitution of the Alcohols

Ethyl alcohol is chosen as a typical example. Analysis and molecular weight determinations indicate that the formula of this substance is $C_2H_6O$. The reaction with sodium (p. 349), whereby one and only one hydrogen atom is replaced, proves that one hydrogen atom differs from the other five. The only way in which this differentiation can be achieved is by linkage through oxygen as represented by the formula



$$\begin{array}{c} \quad\; H \;\; H \\ \quad\; | \;\;\; | \\ H{-}C{-}C{-}O{-}H \\ \quad\; | \;\;\; | \\ \quad\; H \;\; H \end{array}$$

This formula indicates that the alcohol contains the hydroxyl (OH) group. The presence of this group in alcohols is confirmed by their preparation from alkyl halides and potassium hydroxide, and by their reaction with phosphorus chlorides. The alcohols may therefore be regarded as derivatives of water in which one hydrogen atom has been replaced by an alkyl radical.

$$H{-}O{-}H \qquad\qquad C_2H_5{-}O{-}H$$

## General Methods of Preparation of the Alcohols

(1) Alcohols may be prepared from the corresponding halide by hydrolysis with aqueous potash or moist silver oxide.

$$KOH + CH_3Br = CH_3OH + KBr$$
$$AgOH + C_2H_5I = AgI + C_2H_5OH$$

(2) They may be prepared by hydrolysis of the corresponding ester (p. 395).

$$\underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5} + H_2O = \underset{\text{Acetic acid}}{CH_3.COOH} + \underset{\text{Ethyl alcohol}}{C_2H_5OH}$$

(3) They may be prepared by reduction of the corresponding aldehyde or ketone (p. 371).

(4) They may be prepared from the corresponding primary amine by reaction with nitrous acid (p. 433).

$$C_2H_5NH_2 + HNO_2 = N_2 + H_2O + C_2H_5OH$$

(5) The lower alcohols are prepared by special methods (pp. 354, 355).

(6) Any alcohol may be prepared from a suitable magnesium alkyl halide (p. 475).

## Physical Properties of the Alcohols

The homologous series of the monohydric alcohols show the usual gradual rise in boiling and melting points with increase in molecular weight. The lowest alcohols are volatile liquids, the higher members are solids. Methyl, ethyl, and propyl alcohols are miscible with water in all proportions, but the solubility rapidly diminishes as the number of carbon atoms in the molecule increases. The higher members are practically insoluble. As solvents for other substances, the lower alcohols are intermediate between water and non-ionizing solvents such as the paraffin hydrocarbons.

## Chemical Properties of the Alcohols

The following reactions are characteristic of the hydroxyl group, and are given by all the aliphatic alcohols.

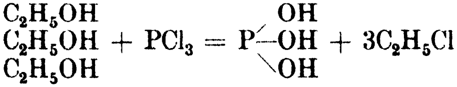
(1) The hydrogen atom of the hydroxyl group is much more reactive than a hydrogen atom attached directly to carbon. It is, for example, easily replaced by the metals sodium or potassium. These metals react with alcohols evolving hydrogen.

$$2C_2H_5OH + 2Na = \underset{\text{Sodium ethoxide}}{2C_2H_5ONa} + H_2$$

The compounds formed are called the alkoxides, e g. sodium methoxide, potassium ethoxide, etc. They react readily with water regenerating the alcohol.

$$C_2H_5ONa + H_2O = C_2H_5OH + NaOH$$

(2) Phosphorus halides (e.g. phosphorus trichloride or phosphorus pentachloride) react with substances containing a hydroxyl group to replace that group by a halogen atom (p. 208). The alcohols react with phosphorus trichloride and pentachloride to give the alkyl halide. The reaction may be compared with the action of the phosphorus compounds on water.

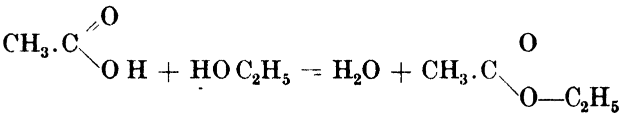


$$\begin{array}{l}C_2H_5OH\\C_2H_5OH\\C_2H_5OH\end{array} + PCl_3 = P\begin{array}{l}\diagup OH\\-OH\\\diagdown OH\end{array} + 3C_2H_5Cl$$

$$3HOH + PCl_3 = H_3PO_3 + 3HCl$$

(3) Alcohols react with acids to form compounds which are called *esters.* For example, ethyl alcohol reacts with acetic acid to form ethyl acetate and water.

$$CH_3.COOH + C_2H_5OH = CH_3.COOC_2H_5 + H_2O$$



$$CH_3.C\begin{matrix}{/\!\!/}O\\ \diagdown OH\end{matrix} + HOC_2H_5 = H_2O + CH_3.C\begin{matrix}{/\!\!/}O\\ \diagdown O-C_2H_5\end{matrix}$$

This reaction, which is called *esterification,* proceeds very slowly, and as it is normally reversible a state of chemical equilibrium is eventually reached (p. 24). Complete conversion of the alcohol into ester can only be achieved by carrying out the reaction in the presence of a dehydrating agent which removes the water formed by the reaction and so enables it to proceed to completion. The common dehydrating agent is concentrated sulphuric acid. An alternative method is to pass gaseous hydrogen chloride into a mixture of the alcohol and acid.

The process of esterification between an alcohol and an acid is often compared with that of salt formation between a base and an acid thus

$$\underset{\text{Acetic}}{CH_3.COOH} + \underset{\text{Ethyl alcohol}}{C_2H_5OH} = \underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5} + H_2O$$

$$CH_3.COOH + NaOH = \underset{\text{Sodium acetate}}{CH_3.COONa} + H_2O$$

But when making this comparison it must be remembered first that esterification is essentially a non-ionic reaction, while salt formation is ionic. (The former reaction is therefore slow, the latter practically instantaneous.) Secondly, the esters are neutral non-ionic substances insoluble in water, and quite unlike salts in their general characteristics.

Esterification is not restricted to reactions between an alcohol and organic acids, as alcohols form esters with inorganic acids, e.g. ethyl alcohol and sulphuric acid form ethyl hydrogen sulphate.

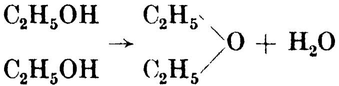
$$C_2H_5OH + H_2SO_4 = C_2H_5HSO_4 + H_2O$$

Similarly with hydrochloric acid the alcohols give alkyl chlorides.

$$C_2H_5OH + HCl = \underset{\text{Ethyl chloride}}{C_2H_5Cl} + H_2O$$

The alkyl halides may therefore be regarded as esters of the halogen acids, and they possess certain properties comparable with those of esters of other acids, e.g. they are commonly prepared by reaction of the alcohol and halogen acid. In addition, the alkyl halides take part in many reactions characteristic only of themselves.

(4) Alcohols react with dehydrating agents to form *ethers* (p. 365) and ethylenic compounds. Concentrated sulphuric acid is usually used as the dehydrating agent; and with ethyl alcohol, the products are diethyl ether at 140°C with the alcohol in excess, or ethylene at 180°C with excess sulphuric acid.



$$\begin{matrix} C_2H_5OH \\ C_2H_5OH \end{matrix} \rightarrow \begin{matrix} C_2H_5 \\ C_2H_5 \end{matrix}\!\!>O + H_2O$$

Diethyl ether

$$CH_3.CH_2OH \rightarrow \underset{\text{Ethylene}}{CH_2{=}CH_2} + H_2O$$

These reactions are the final results of a series of consecutive reactions. The first product of the reaction of ethyl alcohol and sulphuric acid is ethyl hydrogen sulphate.

$$C_2H_5OH + H_2SO_4 = C_2H_5HSO_4 + H_2O$$

This substance is formed readily at a temperature about 100°C, but on further heating in presence of excess alcohol, it reacts to form ether.

$$C_2H_5HSO_4 + C_2H_5OH = (C_2H_5)_2O + H_2SO_4$$

The sulphuric acid is regenerated and may then be used to convert further quantities of alcohol to ether. At a higher temperature, in the absence of further quantities of alcohol, the ethyl hydrogen sulphate decomposes to form ethylene and sulphuric acid.

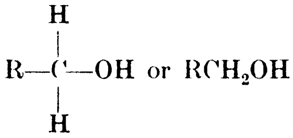
$$C_2H_5HSO_4 = C_2H_4 + H_2SO_4$$

These reactions are the basis of the laboratory preparations of ether and ethylene and the manufacturing process for ether.

## The Behaviour of Alcohols on Oxidation

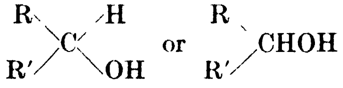
The behaviour of an alcohol towards oxidizing agents depends on its constitution. There are three classes of alcohols each of which behaves differently on oxidation. The classes are distinguished by the number of atoms of hydrogen united to the carbon atom to which the hydroxyl group is attached. One of the four valencies of the carbon atom is linked to the hydroxyl group, three valencies remain which can be linked either to alkyl groups (or substituted alkyl groups) or to hydrogen atoms.

A *primary* alcohol contains the hydroxyl group attached to a carbon atom which is attached to *two* hydrogen atoms and one alkyl group, thus—

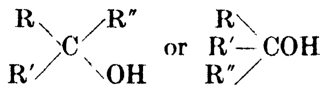


$$R-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-OH \text{ or } RCH_2OH$$

where R represents the alkyl group. A *secondary* alcohol contains one hydrogen atom attached to the carbon atom to which the hydroxyl group is attached.



while in a *tertiary* alcohol the carbon atom is linked to three alkyl groups and the hydroxyl group,

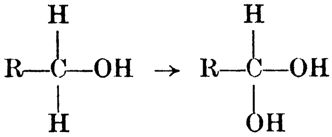


where R, R′, R″ represent alkyl groups which may or may not be identical with one another.

### *Oxidation of Primary Alcohols*

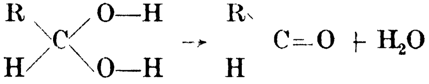
Oxidation of the alcohols proceeds by the conversion of a

C—H linkage to a C—OH linkage. The first stage in the oxidation of a primary alcohol is therefore represented by



$$\mathrm{R{-}\overset{H}{\underset{H}{C}}{-}OH \rightarrow R{-}\overset{H}{\underset{OH}{C}}{-}OH}$$

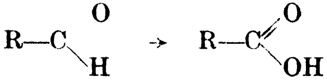
This first product is unstable (it is a general rule that two hydroxyl groups attached to the same carbon atom do not form a stable system), water is split off, and a compound is formed which contains a carbon atom linked to an oxygen atom by a double bond. (The C=O group is called the *carbonyl* group.)

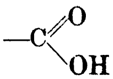


The compound thus formed from a primary alcohol contains a carbon atom united to a hydrogen atom and a doubly linked oxygen atom. It may be represented by the general formula RCHO. (This formula must be distinguished from RCOH, which would indicate the existence of the hydroxyl group.) Substances containing the CHO group are called *aldehydes.*

The first product obtained by the oxidation of a primary alcohol is therefore an aldehyde.

The aldehyde can itself be oxidized, for the hydrogen of the CHO group can be oxidized into the hydroxyl group thus—



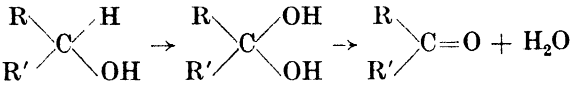
The substances formed by the oxidation of aldehydes are the organic *acids* which contain the group  usually written COOH. This group is called the *carboxyl* group.

No further oxidation is possible unless the acid molecule is completely broken up. The primary alcohols are therefore oxidized in two stages, first to aldehydes and then to acids.

| $CH_3.CH_2OH$ → | $CH_3.CHO$ → | $CH_3.COOH$ |
|---|---|---|
| Ethyl alcohol | Acetaldehyde | Acetic acid |

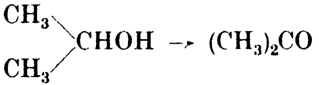
### *Oxidation of Secondary Alcohols*

When the hydrogen of a secondary alcohol is oxidized and converted into a hydroxyl linkage, the compound obtained possesses two hydroxyl groups attached to the same carbon atom. It is unstable, and on losing water the resultant compound is a *ketone*.



$$\begin{matrix}\mathrm{R} & & \mathrm{H}\\ & \mathrm{C} & \\ \mathrm{R'} & & \mathrm{OH}\end{matrix} \rightarrow \begin{matrix}\mathrm{R} & & \mathrm{OH}\\ & \mathrm{C} & \\ \mathrm{R'} & & \mathrm{OH}\end{matrix} \rightarrow \begin{matrix}\mathrm{R} & \\ & \mathrm{C{=}O} \\ \mathrm{R'} & \end{matrix} + \mathrm{H_2O}$$

Ketones contain a carbonyl (CO) group, but unlike the aldehydes contain no hydrogen atom attached to the carbonyl carbon atom. They cannot be oxidized without breaking down the molecule into smaller fragments. A secondary alcohol is oxidized to a ketone, but cannot be oxidized further without breaking down.



$$\begin{matrix}\mathrm{CH_3} & \\ & \mathrm{CHOH} \\ \mathrm{CH_3} & \end{matrix} \rightarrow (\mathrm{CH_3})_2\mathrm{CO}$$

Isopropyl alcohol Acetone

### *Oxidation of a Tertiary Alcohol*

The tertiary alcohols do not possess a hydrogen atom attached to the same carbon atom as the hydroxyl group. They are therefore not oxidizable without the molecule being broken down into smaller fragments.

## **Methyl Alcohol** (Methanol)

The lowest member of the homologous series of alcohols is obtained on a large scale from two sources.

(1) When wood is destructively distilled, the following products are obtained: (*a*) an inflammable gas, (*b*) a watery liquid, (*c*) wood tar, and (*d*) a residue of charcoal in the retort. The aqueous liquid contains acetone, acetic acid, and methyl alcohol. The acetic acid is separated from the mixture (p. 387), and then acetone and methyl alcohol are separated by fractional distillation. The impure methyl alcohol thus obtained is called "wood spirit" or "wood naphtha." It is difficult to separate the two liquids completely, and to obtain pure methyl alcohol some chemical method of removing the acetone is

necessary, e.g. by treatment with chlorine, which reacts with acetone but not methyl alcohol, or by addition of calcium chloride with which methyl alcohol forms a solid crystalline compound ($CaCl_2, 4CH_3OH$).

(2) Methyl alcohol is manufactured on a large scale by a synthetic reaction by passing a mixture of carbon monoxide and hydrogen over a catalyst (zinc and chromium oxides) at 400°C and at a pressure of 100–200 atmospheres. Combination occurs to form methyl alcohol.

$$CO + 2H_2 = CH_3OH$$

(By the use of other catalysts and different conditions of temperature and pressure, higher alcohols may be obtained from these two gases.)

Methyl alcohol is used in the preparation of other important organic substances (e.g. formaldehyde), and to "denature" ethyl alcohol to form methylated spirit, Industrial Methylated Spirit containing 1 vol. of "wood naphtha" to 19 vol. of alcohol.

Methyl alcohol is a colourless liquid (b.p. 67°C) with a characteristic odour. It is completely miscible with water. Pure methyl alcohol may be distinguished from ethyl alcohol as it does not form iodoform by reaction with an alkaline solution of iodine.

### **Ethyl Alcohol** (Ethanol)

The chief source of ethyl alcohol is the fermentation of sugars by yeast, although manufacture by catalytic reactions [particularly the reduction of acetaldehyde (p. 371) by hydrogen] is also used.

The two substances from which ethyl alcohol is manufactured by fermentation are cane sugar (p. 461) and starch (p. 464). The former is present in sugar molasses (the residues from the recovery of cane or beet sugar), the latter in potatoes and various grains, e.g. barley and maize.

Cane sugar (sucrose) and starch are not directly fermentable by yeast, but after hydrolysis into simple sugars, e.g. glucose (p. 457) they can be fermented.

$$\underset{\text{Sucrose}}{C_{12}H_{22}O_{11}} + H_2O = \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Fructose}}{C_6H_{12}O_6}$$

$$\underset{\text{Starch}}{(C_6H_{10}O_5)_n} + nH_2O = \underset{\text{Glucose}}{nC_6H_{12}O_6}$$

The reactions taking place during the fermentation of the simple sugars may be summarized by means of the equation—

$$C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2$$

### THE CHEMICAL REACTIONS TAKING PLACE DURING FERMENTATION.

At first it was believed that alcoholic fermentation was a result of the active life of the yeast cells, and was consequently unable to take place apart from these cells. It was shown, however, by *Buchner* that the liquid obtained from the cells by pressure was as capable of causing fermentation as the yeast itself, although the liquid was quite free from living cells. The fermentation is due to the presence of an *enzyme* in this liquid (the enzyme is called zymase). The yeast cells act as producers of this enzyme and another enzyme (called invertase) which is responsible for the preliminary hydrolysis of cane sugar into fermentable glucose and frutose. Starch can be hydrolyzed, prior to its fermentation, by the enzymes diastase (produced during the germination of barley) and maltase, present in yeast. Thus the full scheme can be summarized as follows—

$$\text{Starch} \xrightarrow{\text{Diastase}} \text{maltose} \xrightarrow{\text{Maltase}} \text{glucose} \xrightarrow{\text{Zymase}} \text{ethyl alcohol} + \text{carbon dioxide.}$$

### *Enzymes and the Mechanism of Enzyme Action*

An enzyme is a complex nitrogenous colloidal substance, which acts as a very efficient catalyst for certain reactions in aqueous media. Enzymes are especially important in the chemical reactions taking place in living organisms, e.g. the digestion of foods, etc.

Enzymes are very specific in their catalytic reactivity, and normally one enzyme will only bring about one type of reaction, e.g. one will hydrolyze esters, another will hydrolyze glucosides, etc. Their catalytic activity is also sensitive to temperature (the activity reaches a maximum at a definite temperature above which the enzymes may be destroyed), and the addition of other substances to the solution (e.g. there is a certain value of the $p$H of the solution for maximum activity).

The mechanism of enzyme action is most easily explained on the assumption that enzymes have a small specific group, which is responsible for the catalytic activity, attached to a large inert colloidal carrier. The first stage of the reaction is the diffusion of the molecule which is being converted by the enzyme to the active group of the enzyme, where it forms a compound. This compound then breaks down into the products of the reaction, regenerating the enzyme which is then able to bring about the conversion of another molecule. The products of the reaction diffuse away from the enzyme. On this interpretation, the velocity of diffusion is an important factor in determining the velocity of an enzyme reaction. This is in agreement with experimental observations.

### *Intermediate Products during Alcohol Fermentation*

It has been realized for a long time that the change from glucose to ethyl alcohol does not proceed directly but by a series of chemical reactions taking place consecutively. The most satisfactory simple scheme was suggested by Neuberg; this scheme is represented by the following equations—

$$\underset{\text{Glucose}}{C_6H_{12}O_6} = \underset{\text{Pyruvic acid}}{2CH_3.CO.COOH} + 4H \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\underset{\text{Pyruvic acid}}{2CH_3.CO.COOH} = \underset{\text{Acetaldehyde}}{2CH_3.CHO} + 2CO_2 \quad . \quad . \quad . \quad . \quad (2)$$

$$2CH_3.CHO + 4H = 2C_2H_5OH \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

[Reaction (2) is brought about by a third enzyme (carboxylase) present in yeast.]

This scheme was confirmed by the isolation of the intermediate products from fermentation mixtures, and by studies on the effect of modifying the reaction conditions. Thus by the addition of sodium sulphite which combines with acetaldehyde and removes it as fast as it is formed, the course of the fermentation is completely altered. The acetaldehyde is no longer able to take up the hydrogen (equation 3), ethyl alcohol cannot be formed and glycerol is formed instead. Later workers have shown that the formation of pyruvic acid occurs as the result of a series of consecutive reactions. The glycerol is obtained by the reduction of one of the intermediate products in the formation of pyruvic acid. This modification of the fermentation process has been used as a source of glycerol (p. 363).

## The Manufacturing Process for Ethyl Alcohol

The first stage in the preparation of alcohol from barley is the conversion of the starch into fermentable sugars. This is done by hydrolysis by the enzyme, diastase. The diastase is formed during the germination of barley and its conversion into *malt*.

The barley is steeped in water for two or three days at a temperature of 10–13°C (50–55°F). The steeped barley is then spread on trays, and allowed to germinate. When it has grown sufficiently, the temperature is raised to kill the growing grain. During the germination of the barley diastase is formed, and a small fraction (10 per cent) of the starch is converted into sugar, while the cell walls of the other starch grains are partially broken down so that the starch is more easily attacked during the next process. The malt is then dried and ground, and mixed with water in mash tuns. (Fresh starch may be added either as unmalted corn or as potato paste.) The starch is converted by the diastase into fermentable sugars which dissolve in the water, and are separated from the insoluble residues.

The official *Extract of Malt* is obtained from the aqueous extract obtained from malt by evaporation under reduced pressure at a fairly low temperature. It is specified that it should contain 4·0 per cent protein nitrogen. The nitrogen is determined by the *Kjeldahl* method (p. 200).

The fermentation of the aqueous extract of the malt is carried out by seeding with yeast and allowing to stand at a controlled temperature. (Molasses can be fermented directly by seeding with yeast without previous treatment.) Frothing occurs, due to the evolution of carbon dioxide, and the fermentation is continued for some days. The maximum concentration of alcohol obtainable by a simple fermentation is about 18 per cent, above which the yeast cells are unable to live.

The fermented liquor is then distilled, and alcohol up to 95 per cent concentration is obtained. The residue in the still contains practically all the proteins present in the original materials, and may be used as a cattle food. The distilled alcohol contains varying quantities of higher alcohols (fusel oil), and these impart a characteristic taste to the distilled product. They may be separated from the ethyl alcohol by redistillation, but the water cannot be separated completely in this way as a constant boiling mixture is obtained.

## PREPARATION OF ANHYDROUS ALCOHOL

As it is impossible to separate water from alcohol completely by distillation, some other method must be used for the manufacture of anhydrous alcohol. Previously the wet alcohol was distilled from a dehydrating agent such as anhydrous copper sulphate or quicklime.

A better and cheaper separation is now obtained by taking advantage of the fact that a system containing alcohol, water, and petroleum ether (b.p. 70–90°C) forms a constant boiling mixture containing all three substances which boils at a lower temperature than any single constituent. Commercially, a mixture of petroleum ether (benzine) and benzene is added to the moist alcohol, and the mixture is distilled. The first fraction contains the whole of the water, a little alcohol and some of the petroleum ether-benzene mixture. After the whole of the water has been removed the second runnings distil, consisting of the remainder of the petroleum ether-benzene mixture, together with alcohol. Finally pure anhydrous alcohol distils.

## PROPERTIES AND CONTROL OF PURITY OF ETHYL ALCOHOL

Ethyl alcohol is a mobile liquid (b.p. 78°C), miscible in all proportions with water and chloroform. When dehydrated, it does not restore the blue colour to anhydrous copper sulphate. The formation of iodoform by the action of iodine in alkaline solution is a sensitive test for the presence of ethyl alcohol. (The presence of alcohol in Ethyl Chloride is detected officially by this test.)

Alcohol (which contains officially between 92·0 and 92·7 per cent w/w of $C_2H_6O$) is tested officially for undue acidity or alkalinity, and for the presence of (1) oily and resinous substances which are insoluble in water; (2) fusel oil, whose odour can be detected on evaporation, and which gives a reddish brown colour with sulphuric acid; (3) acetaldehyde which polymerizes to a yellowish brown resin under the action of alkalies (p. 374).

The test for methyl alcohol depends on its oxidation to formaldehyde which gives a violet colour with Schiff's reagent. Acetaldehyde which is formed when ethyl alcohol is oxidized does not interfere with the test, as it does not give a colour with Schiff's reagent in the presence of sulphuric acid (possibly owing to its conversion to a non-aldehydic polymer induced by the presence of the acid). The test is carried out by oxidizing with a solution of potassium permanganate in phosphoric acid. The excess permanganate is decolorized by adding a solution of oxalic and sulphuric acids, and the formaldehyde is tested for with Schiff's reagent (decolorized magenta solution). Under the conditions of the test, pure ethyl alcohol forms a colourless solution, but Industrial Methylated Spirit forms a deep violet colour.

The compositions of the dilute aqueous alcohols are measured by determinations of specific gravity and refractive index. These processes are also used for the determination of the alcohol contents of tinctures, etc. (p. 106).

*N. Propyl Alcohol* (propanol, $CH_3.CH_2.CH_2OH$) is obtained by the fractional distillation of fusel oil.

*Isopropyl Alcohol* ( $(CH_3)_2CHOH$) is obtained by the reduction of acetone or from propylene and is used industrially as a substitute for ethyl alcohol. It may be distinguished from it as it forms iodoform in the cold with alkaline iodine solutions.

*N. Butyl Alcohol* (butanol, $CH_3.CH_2.CH_2.CH_2OH$) is manufactured by the catalytic reduction of crotonaldehyde (which is prepared from acetaldehyde). It can also be obtained by a special fermentation process. The esters of butyl alcohol are important industrial solvents.

*Isobutyl Alcohol* ( $(CH_3)_2.CH.CH_2OH$) is obtained from fusel oil by fractional distillation.

*Amyl Alcohol.* Isoamyl alcohol is the chief constituent of fusel oil. The formula of this alcohol is $(CH_3)_2CH.CH_2.CH_2OH$. The optically active amyl alcohol $[CH_3.CH_2.CH(CH_3).CH_2OH]$ is also present in fusel oil. Amyl alcohol and its esters are valuable solvents.

*Amylene Hydrate* is ( $(CH_3)_2.C(OH).CH_2.CH_3$) and is obtained by the addition of water to amylene by the action of boiling aqueous sulphuric acid.

$$\underset{\text{Amylene}}{(CH_3)_2C{=}CH.CH_3} + H_2O \rightarrow \underset{\text{Amylene hydrate}}{(CH_3)_2.C(OH).CH_2.CH_3}$$

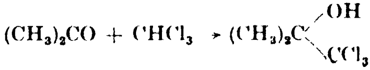
Amylene itself is obtained by the dehydration of ordinary amyl alcohol, e.g. by heating with anhydrous zinc chloride.

$$(CH_3)_2.CH.CH_2.CH_2OH \rightarrow H_2O + (CH_3)_2CH.CH{=}CH_2$$
$$\rightarrow (CH_3)_2C{=}CH.CH_3$$

*Cetostearyl Alcohol* is a mixture of alcohols of the paraffin series obtained from sperm oils (which contain cetyl palmitate as a principal constituent) or from the corresponding acids by reduction. The chief components are cetyl alcohol, $CH_3(CH_2)_{14}CH_2OH$, and stearyl alcohol, $CH_3(CH_2)_{16}CH_2OH$.

*Tribromo-ethyl Alcohol* ($CBr_3.CH_2OH$) is obtained by the reduction of its corresponding aldehyde (bromal) (p. 378). As an alkyl halide derivative, it does not itself react directly with silver nitrate, but it is hydrolyzed by alkalis, forming a metallic bromide which reacts with silver nitrate. This reaction is used officially for an identity test and an assay process. Its solution in Amylene Hydrate is Bromethol.

*Chlorbutol* is the tri-chlor derivative of tertiary butyl alcohol. It is obtained by the addition of chloroform to acetone in presence of potassium hydroxide. The reaction is slowly reversed in presence of water.

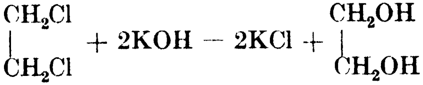


$$(CH_3)_2CO + CHCl_3 \rightarrow (CH_3)_2C\begin{cases} OH \\ CCl_3 \end{cases}$$

## Alcohols Containing more than One Hydroxyl Group

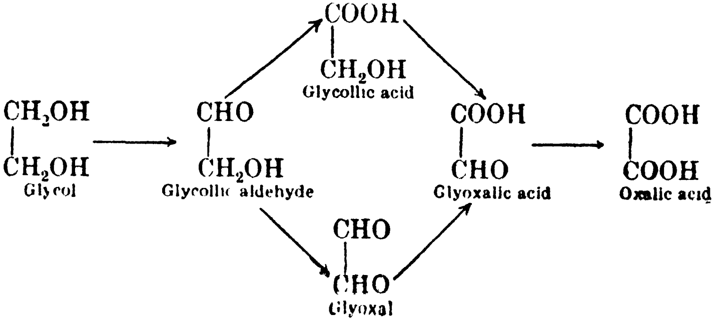
The alcohols which contain more than one hydroxyl group are called *polyhydric* alcohols; those with two hydroxyl groups are the *dihydric* alcohols (these are also called as a class the *glycols*), those with three hydroxyl groups are the *trihydric* alcohols, etc.

These alcohols can be prepared by suitable modifications of the general methods of preparation as given for the monohydric alcohols. For example, the hydrolysis of ethylene dichloride with aqueous potassium hydroxide gives the simplest dihydric alcohol which is called glycol or ethylene glycol.

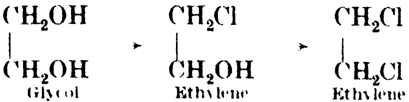


$$\begin{array}{l} CH_2Cl \\ | \\ CH_2Cl \end{array} + 2KOH - 2KCl + \begin{array}{l} CH_2OH \\ | \\ CH_2OH \end{array}$$

The properties of the polyhydric alcohols correspond with those of the monohydric alcohols; though a greater number of derivatives may be obtained from them, as either one, or any number or combination of the hydroxyl groups can be made to react; e.g. the oxidation of glycol can be made to furnish the following products—



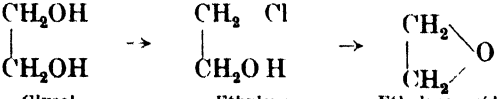
Similarly, glycol reacts with gaseous hydrogen chloride to give successively ethylene chlorohydrin and ethylene dichloride.



$$\begin{array}{l} CH_2OH \\ | \\ CH_2OH \end{array} \rightarrow \begin{array}{l} CH_2Cl \\ | \\ CH_2OH \end{array} \rightarrow \begin{array}{l} CH_2Cl \\ | \\ CH_2Cl \end{array}$$

Glycol Ethylene chlorohydrin Ethylene dichloride

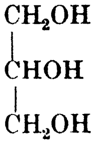
The glycols possess an additional property not shared by the monohydric alcohols; they yield anhydrides by the elimination of water between the two hydroxyl groups. The anhydride of glycol (best obtained from the monochloride ester of glycol) is called ethylene oxide (p. 331).



Glycol Ethylene chlorhydrin Ethylene oxide

**Glycerol** (or Glycerin)

The most important representative of the class of trihydric alcohols is glycerol. The formula of glycerol is



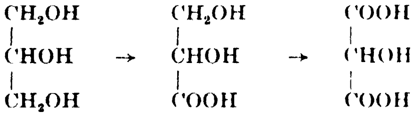
$$\begin{array}{l} CH_2OH \\ | \\ CHOH \\ | \\ CH_2OH \end{array}$$

### THE FORMULA OF GLYCEROL

The formula of glycerol has been deduced as follows. It has been confirmed by synthesis (p. 469).

(1) Glycerol contains three hydroxyl groups as is indicated by the fact that it forms mono-, di-, and tri-esters.

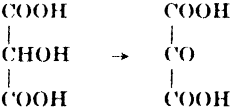
(2) Two of these hydroxyl groups are primary alcoholic groups, since they can be oxidized through aldehydes to acids. When one primary alcoholic group of glycerol is oxidized, the product is glyceric acid. On oxidation of the other group, tartronic acid is formed.



$$\begin{array}{lcl cl} CH_2OH & & CH_2OH & & COOH \\ | & & | & & | \\ CHOH & \rightarrow & CHOH & \rightarrow & CHOH \\ | & & | & & | \\ CH_2OH & & COOH & & COOH \end{array}$$

Glycerol Glyceric acid Tartronic acid

(3) The third hydroxyl group is a secondary alcoholic group, for tartronic acid can be oxidized to a ketonic acid.



$$\begin{array}{lcl} COOH & & COOH \\ | & & | \\ CHOH & \rightarrow & CO \\ | & & | \\ COOH & & COOH \end{array}$$

Mesoxalic acid

### PREPARATION OF GLYCEROL

Glycerol can be prepared by suitable modifications of the general methods for monohydric alcohols. It is obtained on a large scale from fats and fatty oils, which are the esters of glycerol and certain organic acids (p. 398). The fats are converted into the acids and glycerol by hydrolysis (normally in alkaline solution in the manufacture of soap). After separation of the soap and any resinous matter, a watery liquid is obtained which contains the glycerol and sodium chloride. The glycerol is extracted by distillation *in vacuo* after a preliminary concentration by evaporation *in vacuo.*

Glycerol is also obtained (together with the free fatty acid) by hydrolysis of fats by water or superheated steam under pressure.

When larger quantities of glycerol than are normally obtainable in this way were needed for the manufacture of explosives, supplies were obtained by a modification of the fermentation process. By carrying out the fermentation of sugar in the presence of sodium sulphite, large quantities of glycerol are formed instead of alcohol (p. 357).

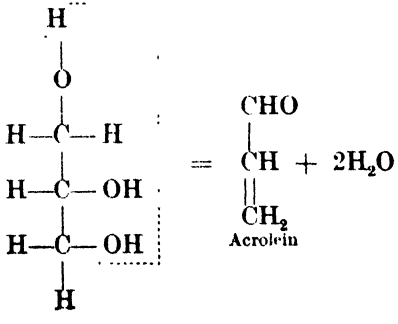
### PROPERTIES AND CONTROL OF PURITY OF GLYCERIN B.P.

Glycerin is a colourless syrupy liquid which is hygroscopic. It crystallizes on standing at low temperatures (m.p. 20°C). Tests are made officially for the presence of (1) reducing substances (e.g. acrolein) by the addition of ammoniacal silver nitrate, (2) fatty acids, (3) sugars (added as adulterant) which are readily carbonizable, and (4) copper and iron. The iron test depends on the colour produced on addition of tannic acid.

### CHEMICAL PROPERTIES OF GLYCEROL

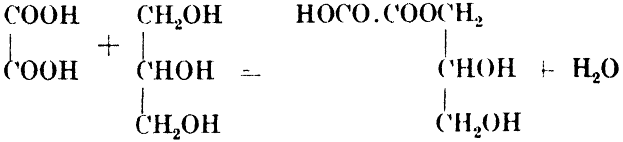
In addition to the general properties of alcohols the following special properties are important.

(1) By the action of dehydrating agents (e.g. concentrated sulphuric acid or potassium bisulphate) two molecules of water are removed from the molecule of glycerol. The substance formed is an unsaturated aldehyde *acrolein*, which has a characteristic smell and lachrymatory action.



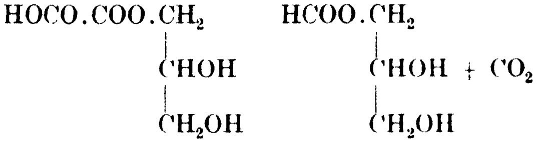
(2) Acrolein is the aldehyde corresponding to the unsaturated alcohol $CH_2{=}CH.CH_2OH$, which is called *allyl alcohol*. Allyl alcohol can be obtained from glycerol by reaction with oxalic acid. By another reaction between the same two substances formic acid can be prepared.

The first product of the reaction between oxalic acid and glycerol is the mono-ester (glyceryl monoxalate).



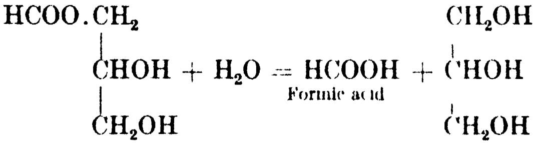
$$\begin{array}{l}\mathrm{COOH}\\|\\\mathrm{COOH}\end{array} + \begin{array}{l}\mathrm{CH_2OH}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array} = \begin{array}{r}\mathrm{HOCO.COOCH_2}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array} + \mathrm{H_2O}$$

This substance loses carbon dioxide on heating, and is transformed into the monoglyceryl ester of formic acid (often called monoformin).



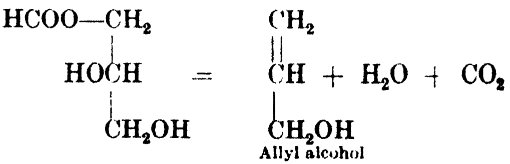
$$\begin{array}{r}\mathrm{HOCO.COO.CH_2}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array} \qquad \begin{array}{r}\mathrm{HCOO.CH_2}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array} + \mathrm{CO_2}$$

On gentle heating with excess oxalic acid (followed by steam distillation) formic acid is obtained by hydrolysis of the ester.



$$\begin{array}{r}\mathrm{HCOO.CH_2}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array} + \mathrm{H_2O} = \underset{\text{Formic acid}}{\mathrm{HCOOH}} + \begin{array}{l}\mathrm{CH_2OH}\\|\\\mathrm{CHOH}\\|\\\mathrm{CH_2OH}\end{array}$$

On heating to a higher temperature and if excess glycerol is present, the ester breaks down and allyl alcohol is obtained



$$\begin{array}{r}\mathrm{HCOO{-}CH_2}\\|\\\mathrm{HOCH}\\|\\\mathrm{CH_2OH}\end{array} = \underset{\text{Allyl alcohol}}{\begin{array}{l}\mathrm{CH_2}\\\|\\\mathrm{CH}\\|\\\mathrm{CH_2OH}\end{array}} + \mathrm{H_2O} + \mathrm{CO_2}$$

(3) The nitric acid esters of glycerol are highly explosive (nitroglycerin). They are described with other esters on p. 396.

## THE ALIPHATIC ETHERS

Alcohols have been regarded as derivatives of water, in which one hydrogen atom has been replaced by an alkyl group. Ethers are obtained when both the hydrogen atoms of water are replaced by organic radicals.

$$\underset{\text{Water}}{H{-}O{-}H} \qquad \underset{\text{Methyl alcohol}}{CH_3{-}O{-}H} \qquad \underset{\text{Dimethyl ether}}{CH_3{-}O{-}CH_3}$$

The radicals replacing the two hydrogen atoms need not be identical, the ethers formed from two dissimilar radicals being known as *mixed ethers* in distinction to *simple ethers* where the two radicals are the same.

$$\underset{\substack{\text{Diethyl ether}\\ \text{(simple ether)}}}{C_2H_5{-}O{-}C_2H_5} \qquad \underset{\substack{\text{Methyl ethyl ether}\\ \text{(mixed ether)}}}{CH_3{-}O{-}C_2H_5}$$

Diethyl ether ($C_2H_5{-}O{-}C_2H_5$) and methyl propyl ether ($CH_3{-}O{-}C_3H_7$) are isomeric. A similar type of isomerism, due to the difference in chain length of the two alkyl groups is found in many other classes of organic compounds (e.g. ketones, esters). It is sometimes called *metamerism*.

**Preparation of Ethers**

The two most important methods of preparation of ethers are—

(1) By the action of sulphuric acid on alcohols. Dehydration takes place and ethers are obtained.

$$\begin{matrix} C_2H_5{-}O{-}H \\ C_2H_5{-}O{-}H \end{matrix} = C_2H_5{-}O{-}C_2H_5 + H_2O$$

(If the conditions of the reaction are not controlled other reactions take place which have already been described on p. 351.)

This reaction can be used for the preparation of mixed ethers if sulphuric acid is made to react on an equal mixture of two different alcohols.

$$C_2H_5O\,H + H\underset{\cdot\cdot}{O}\,CH_3 = C_2H_5{-}O{-}CH_3 + H_2O$$

(2) By reacting on an alkyl halide with the sodium derivative of an alcohol.

$$C_2H_5{-}O{-}Na + C_2H_5I = C_2H_5{-}O{-}C_2H_5 + NaI$$

This reaction can be adopted for the preparation of mixed ethers.

$$CH_3I + C_2H_5{-}O{-}Na = NaI + CH_3{-}O{-}C_2H_5$$

This reaction is often called *Williamson's synthesis*, as Williamson discovered it in 1856, and established the constitution of diethyl ether which is given above.

## General Properties of Ethers

Ethers are usually neutral liquids which are characterized by a general chemical inactivity. They are quite stable to dilute acids and alkalis, but some ethers absorb oxygen on standing, forming ether peroxides, whose composition has not been thoroughly established. A possible representation of the composition of the peroxide of di-ethyl ether is $CH_3.CHOH.O.O.CHOH.CH_3$.

These accumulate during distillation in the least volatile fractions and may give rise to violent explosions.

Ethers are decomposed when heated with the constant boiling solution of hydriodic acid.

$$R{-}O{-}R + HI \quad ROH + RI$$

This reaction forms the basis for the determination of the methoxyl ($OCH_3$) content of compounds (cf. e.g. determination of quinine in Totaquine). The substance is heated with the hydriodic acid and the resulting methyl iodide is removed in a stream of carbon dioxide into absorption vessels containing bromine, acetic acid, and potassium acetate. It there reacts to form first iodine monobromide and ultimately iodic acid.

After the excess of bromine in the solutions from the absorption vessels has been removed by adding formic acid, the iodic acid is determined by adding potassium iodide and titrating the liberated iodine with standard thiosulphate solution.

$$ROCH_3 + HI = ROH + CH_3I$$
$$CH_3I + Br_2 = CH_3Br + IBr$$
$$IBr + 2Br_2 + 3H_2O = HIO_3 + 5HBr$$
$$HIO_3 + 5HI = 3I_2 + 3H_2O$$

From the above equations it will be seen that six equivalent weights of iodine are liberated per radical of methoxyl, i.e. 60 litres N/10 thiosulphate ≡ 31 g methoxyl.

Ethers are decomposed by heating with phosphorous pentachloride

$$C_2H_5.O.C_2H_5 + PCl_5 = 2C_2H_5Cl + POCl_3$$

## Diethyl Ether

The most important representative of the class is diethyl ether (often referred to as ether), which is a colourless, volatile, and inflammable liquid (b.p. 36°C) with a characteristic smell. It is prepared from ethyl alcohol and sulphuric acid. If industrial methylated spirit is used the product contains methyl ethyl ether and acetone as well as diethyl ether. It is then called *methylated ether.*

Solvent Ether of the *British Pharmacopœia* is di-ethyl ether; a product of greater purity is included under the name Anæsthetic Ether; this may contain as a preservative a small quantity of hydroquinone, a reducing substance which reacts with ether peroxide. Propyl gallate may also be used as a stabilizer.

Anæsthetic Ether (which is usually prepared from duty-free spirit under licence) is tested for the presence of acetone by the reaction to form a mercury compound with Nessler's reagent. (Nessler's reagent is reduced by acetaldehyde, so that if any is present it would be detected in this test.) A test is also made for the presence of methyl alcohol.

The preparation of ether by the reaction of alcohol with sulphuric acid is theoretically a continuous process, a given quantity of acid being sufficient to convert an unlimited amount of alcohol to ether. These conditions cannot be realized in practice, owing to losses by side reactions. Slight reduction of the sulphuric acid by alcohol would give rise to the presence of sulphurous acid and acetaldehyde. The official test for acidity is carried out by evaporating 20 mils of Ether with 5 mils of freshly boiled and cooled water in a neutral glass vessel. The aqueous solution left after the ether has evaporated should not change the acidity of a methyl red solution from *p*H 5·0 to beyond *p*H 4·9.

The presence of peroxides is controlled by addition of potassium iodide solution. On standing iodine is liberated.

The official tests on Solvent Ether and Anæsthetic Ether are carried out in completely filled stoppered tubes. The yellow colour developed from about 4 mils of Solvent Ether should not be deeper than that corresponding to 0·5 mil of N/1,000 iodine. In the case of Anæsthetic Ether the test is more stringent, and no blue or red colour should be developed in the presence of starch.

*Divinyl Ether* [$(CH_2 = CH)_2O$] is an ether obtained by the following reactions from ethylene chlorohydrin.

$$2CH_2Cl.CH_2OH \rightarrow \underset{\text{Dichlorodiethyl ether}}{CH_2Cl.CH_2.O.CH_2.CH_2Cl} + H_2O$$

$$CH_2Cl.CH_2.O.CH_2.CH_2Cl \rightarrow \underset{\text{Divinyl ether}}{CH_2=CH.O.CH=CH_2} + 2HCl$$

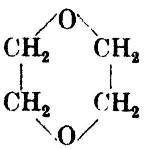
The first dehydration reaction is carried out by treatment with concentrated sulphuric acid, the second (removal of hydrogen halide) by fusion with potassium hydroxide.

Divinyl ether, being unsaturated, is more reactive than other ethers. It reacts immediately with bromine, is slowly oxidized by air to formaldehyde and formic acid (the official substance contains a preservative, e.g. phenyl α naphthylamine), and slowly changes to a jelly as the result of polymerization. Acids cause the formation of acetaldehyde by a hydrolysis reaction.

$$CH_2=CH.O.CH=CH_2 + 2Br_2$$
$$\rightarrow CH_2Br.CHBr.O.CHBr.CH_2Br$$

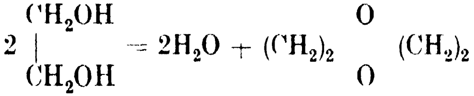
$$CH_2=CH.O.CH=CH_2 + H_2O$$
$$\rightarrow 2(CH_2=CH_2OH) \rightarrow \underset{\text{Acetaldehyde}}{2(CH_3.CHO)}$$

*Dioxan* (diethylene dioxan) is an ether of composition



i.e. ethylene glycol di-ether

It is obtained by dehydrating glycol with concentrated sulphuric acid. It is an oily liquid, miscible with water in all proportions. It forms peroxides somewhat readily.



$$2\begin{array}{l}CH_2OH\\ |\\ CH_2OH\end{array} = 2H_2O + (CH_2)_2\begin{array}{c}O\\ \\ O\end{array}(CH_2)_2$$

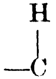
*Ethylene Glycol Mono-ethyl Ether* ($CH_2OH.CH_2OC_2H_5$) may be prepared by the action of sodium ethoxide on ethylene chlorohydrin.

$$CH_2OH.CH_2Cl + NaOC_2H_5 = NaCl + CH_2OH.CH_2OC_2H_5$$

# CHAPTER XXIII

# THE ALDEHYDES AND KETONES

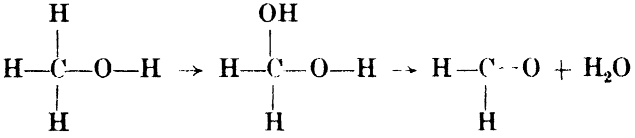
## THE ALIPHATIC ALDEHYDES



THE aldehydes contain the group $-\overset{\displaystyle H}{\overset{|}{C}}=O$ (written CHO).

## General Methods of Preparation of Aldehydes

(1) Aldehydes are prepared by the oxidation of primary alcohols. Thus methyl alcohol on oxidation gives formaldehyde and ethyl alcohol gives acetaldehyde.



$$H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-O-H \rightarrow H-\overset{\displaystyle OH}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-O-H \rightarrow H-\underset{\displaystyle H}{\underset{|}{C}}=O + H_2O$$

Methyl alcohol Formaldehyde

$$CH_3.CH_2OH \rightarrow CH_3.CH(OH)_2 \rightarrow CH_3.CHO + H_2O$$

Ethyl alcohol Acetaldehyde

The commercial preparation of formaldehyde and the laboratory preparation of acetaldehyde depend on these reactions. Formaldehyde is manufactured by oxidizing methyl alcohol vapour by passing it mixed with air over a heated copper catalyst. The oxidizing agent used in the laboratory preparation of acetaldehyde is sodium or potassium dichromate in acid solution. Acetaldehyde is manufactured on the large scale by a special method (p. 377).

(2) Aldehydes may be obtained by the reduction of the corresponding acid or acid chloride, or by heating the calcium salt of the acid with calcium formate (p. 379).

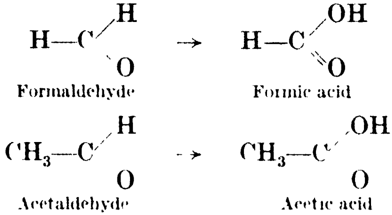
(3) Aldehydes may also be obtained by the hydrolysis of dihalides containing the $CHX_2$ group (cf. p. 518).

$$R.CHX_2 \rightarrow RCH(OH)_2 \rightarrow RCHO$$

## General Properties of Aldehydes

The aldehydes are reactive compounds, some of their reactions being similar to those of ketones.

(1) The aldehydes are easily oxidized to the corresponding acid.



$$\mathrm{H{-}C}\genfrac{}{}{0pt}{}{\diagup \mathrm{H}}{\diagdown \mathrm{O}} \rightarrow \mathrm{H{-}C}\genfrac{}{}{0pt}{}{\diagup \mathrm{OH}}{\diagdown\!\diagdown \mathrm{O}}$$

Formaldehyde → Formic acid

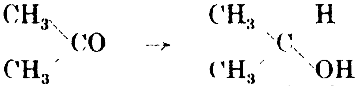
$$\mathrm{CH_3{-}C}\genfrac{}{}{0pt}{}{\diagup \mathrm{H}}{\mathrm{O}} \rightarrow \mathrm{CH_3{-}C}\genfrac{}{}{0pt}{}{\diagup \mathrm{OH}}{\mathrm{O}}$$

Acetaldehyde → Acetic acid

Owing to the ease with which aldehydes are oxidized, they are reducing agents. The reduction of ammoniacal silver nitrate to silver, and Fehling's solution to red cuprous oxide, are commonly used as tests for aldehydes. Ketones are not readily oxidized and are not reducing agents.

(2) Aldehydes are reduced to the corresponding alcohol. (Sodium amalgam and water can be used as a reducing agent, or the vapour of the aldehyde may be passed mixed with hydrogen over a nickel catalyst.) Ketones are usually reduced to the corresponding secondary alcohol.

$$\underset{\text{Acetaldehyde}}{\mathrm{CH_3.CHO}} + \mathrm{H_2} = \underset{\text{Ethyl alcohol}}{\mathrm{CH_3.CH_2OH}}$$



$$\genfrac{}{}{0pt}{}{\mathrm{CH_3}\diagdown}{\mathrm{CH_3}\diagup}\mathrm{CO} \rightarrow \genfrac{}{}{0pt}{}{\mathrm{CH_3}\diagdown}{\mathrm{CH_3}\diagup}\mathrm{C}\genfrac{}{}{0pt}{}{\diagup \mathrm{H}}{\diagdown \mathrm{OH}}$$

Acetone → Isopropyl alcohol

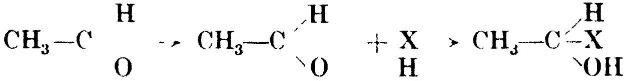
(3) Phosphorus pentachloride reacts with aldehydes to replace the oxygen atom with two chlorine atoms.

$$\mathrm{CH_3.CHO} + \mathrm{PCl_5} = \mathrm{POCl_3} + \underset{\substack{\text{Ethylidene}\\ \text{dichloride}}}{\mathrm{CH_3.CHCl_2}}$$

(Ketones behave in a similar manner.)

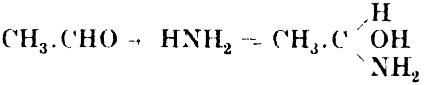
(4) Aldehydes form addition compounds with ammonia, sodium bisulphite, and hydrogen cyanide. These substances all contain hydrogen, which forms a hydroxyl group with the oxygen of the aldehyde, the remainder of the added

molecule becoming united to the aldehyde carbon atom. The reactions can be represented thus—

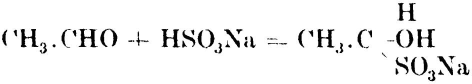
(1) 

$$CH_3{-}C\begin{matrix}H\\ \\ O\end{matrix} \rightarrow CH_3{-}C\begin{matrix}H\\ \\ O\end{matrix} + \begin{matrix}X\\ H\end{matrix} \rightarrow CH_3{-}C\begin{matrix}H\\ X\\ OH\end{matrix}$$

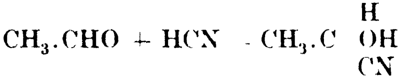
Acetaldehyde

(2) 

$$CH_3.CHO + HNH_2 = CH_3.C\begin{matrix}H\\ OH\\ NH_2\end{matrix}$$

(3) 

$$CH_3.CHO + HSO_3Na = CH_3.C\begin{matrix}H\\ OH\\ SO_3Na\end{matrix}$$

(4) 

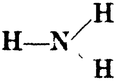
$$CH_3.CHO + HCN = CH_3.C\begin{matrix}H\\ OH\\ CN\end{matrix}$$

The aldehyde-ammonia and bisulphite compounds are often crystalline substances, which are easily decomposed, re-forming the aldehydes. They may be used in the purification of the aldehydes. The hydrogen cyanide addition compounds are called *cyanhydrins*, and they are important as a stage in the synthesis of organic acids. [On hydrolysis the cyanide radical is converted to the carboxyl group (p. 435).]

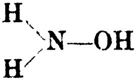
$$\underset{\text{Acetaldehyde cyanhydrin}}{CH_3.CHOH.CN} \rightarrow \underset{\text{Lactic acid}}{CH_3.CHOH.COOH}$$

Ketones react similarly with sodium bisulphite and hydrogen cyanide, but do not form addition compounds with ammonia.

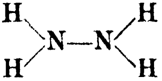
(5) Aldehydes take part in condensation reactions with hydroxylamine and hydrazine or derivatives of hydrazine (especially phenylhydrazine or dinitrophenylhydrazine). Hydroxylamine is the monohydroxyl derivative of ammonia ($NH_2OH$), hydrazine is a derivative of ammonia of the formula $NH_2.NH_2$, while phenylhydrazine is $C_6H_5NH.NH_2$, and dinitrophenylhydrazine is $(NO_2)_2C_6H_3.NH.NH_2$



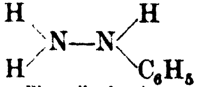
Ammonia



Hydroxylamine



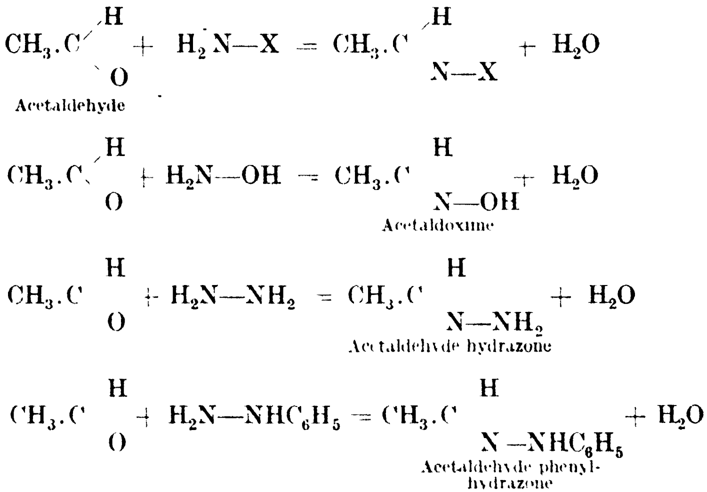
Hydrazine



Phenylhydrazine

A *condensation reaction* involves the union of two molecules accompanied by the elimination of a molecule of water (or in a few cases, other simple molecules such as hydrogen chloride).

These derivatives of ammonia react with the carbonyl group of the aldehyde to replace the $C=O$ link by the $C=N$ linkage, water being eliminated.



$$CH_3.C\begin{matrix}H\\O\end{matrix} + H_2N—X = CH_3.C\begin{matrix}H\\ \\N—X\end{matrix} + H_2O$$

Acetaldehyde

$$CH_3.C\begin{matrix}H\\O\end{matrix} + H_2N—OH = CH_3.C\begin{matrix}H\\ \\N—OH\end{matrix} + H_2O$$

Acetaldoxime

$$CH_3.C\begin{matrix}H\\O\end{matrix} + H_2N—NH_2 = CH_3.C\begin{matrix}H\\ \\N—NH_2\end{matrix} + H_2O$$

Acetaldehyde hydrazone

$$CH_3.C\begin{matrix}H\\O\end{matrix} + H_2N—NHC_6H_5 = CH_3.C\begin{matrix}H\\ \\N—NHC_6H_5\end{matrix} + H_2O$$

Acetaldehyde phenylhydrazone

(Ketones behave with these reagents in a similar manner.)

The derivatives obtained by the reaction of hydroxylamine with an aldehyde or ketone are called *oximes*; the derivatives obtained from hydrazine are called *hydrazones*. These compounds are commonly solid crystalline substances of definite melting point, which can be used for the identification of aldehydes or ketones.

The determination of aldehydes or ketones (e.g. citral, benzaldehyde, cinnamic aldehyde, and carvone in volatile oils) can be effected by reaction with hydroxylamine hydrochloride. On the formation of the oxime, free hydrochloric acid is liberated equivalent to the quantity of aldehyde reacting.

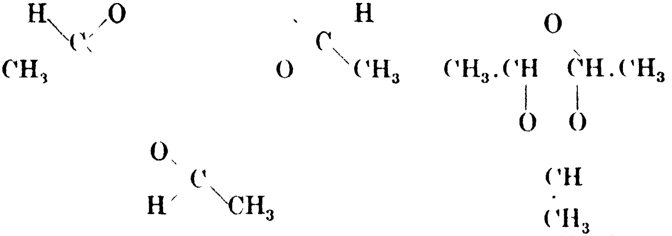
$$RCHO + NH_2OH, HCl \rightarrow R—C=NOH + H_2O + HCl$$

(6) Aldehydes (but not ketones) undergo polymerization reactions very easily. When acetaldehyde is mixed with

concentrated sulphuric or hydrochloric acid, it polymerizes to paraldehyde.

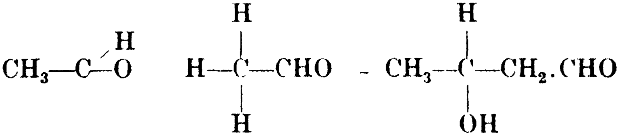
$$\underset{\text{Acetaldehyde}}{3CH_3.CHO} = \underset{\text{Paraldehyde}}{(C_2H_4O)_3}$$

As polymerization takes place through the opening up of the oxygen double bond of each acetaldehyde molecule, the resultant substance does not behave as an aldehyde.



Paraldehyde

A different type of polymerization (the aldol condensation) occurs under the influence of small quantities of alkalis. In this case linkage of two molecules takes place by the migration of a hydrogen atom from the methyl group of one molecule to the oxygen of the other molecule.



The product obtained is called *aldol* (it is an *ald*ehyde and an alcoh*ol*). It loses water readily to form an unsaturated aldehyde.

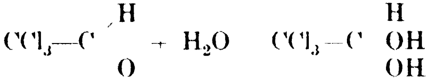
$$\underset{\text{Aldol}}{CH_3.CH(OH).CH_2.CHO} \rightarrow \underset{\text{Crotonic aldehyde}}{CH_3.CH=CH.CHO} + H_2O$$

Crotonic aldehyde is prepared by this reaction on a large scale, for conversion into butyl aldehyde ($CH_3.CH_2.CH_2.CHO$) and thus into butyl alcohol ($CH_3.CH_2.CH_2.CH_2OH$).

Under other conditions aldehydes form more complex polymerization products, e.g. acetaldehyde boiled with strong alkalies polymerizes to a characteristically smelling resin of high molecular weight (aldehyde resin). Acetaldehyde with dilute acids at 0°C polymerizes to a white solid of composition $(C_2H_4O)_4$, to which the name metaldehyde is given. (This substance is used as a solid fuel.) Formaldehyde polymerizes into various sugar-like substances $(CH_2O)_6$, or to other polymeric derivatives called paraformaldehyde and metaformaldehyde.

(7) Aldehydes form a coloured complex compound with a solution of magenta decolorized by sulphur dioxide. This reaction is used as a test for aldehydes (cf. test for methyl alcohol in ethyl alcohol, p. 359).

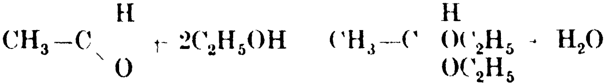
(8) The halogen substituted aldehydes such as chloral ($CCl_3.CHO$) form hydrates by the addition of water. These hydrates are peculiar in that they contain a carbon atom joined to two hydroxyl groups.



$$CCl_3{-}C\begin{matrix}H\\ \\ O\end{matrix} + H_2O \qquad CCl_3{-}C\begin{matrix}H\\ OH\\ OH\end{matrix}$$

Chloral Chloral hydrate

Simple aldehydes do not form hydrates, but derivatives of such hydrates (called *acetals*) are formed by the interaction of aldehydes and alcohols in presence of a dehydrating agent (ketones do not normally form these derivatives).



$$CH_3{-}C\begin{matrix}H\\ \\ O\end{matrix} + 2C_2H_5OH \qquad CH_3{-}C\begin{matrix}H\\ OC_2H_5\\ OC_2H_5\end{matrix} + H_2O$$

Acetal

(9) Aldehydes and ketones combine with magnesium alkyl halides (p. 475).

## Formaldehyde

The simplest aldehyde is a gas possessing a characteristic odour. It is soluble in water, and is normally handled in solution (formalin).

Formaldehyde is prepared commercially by the catalytic oxidation of methyl alcohol vapour by passing it mixed with air over heated copper. The formaldehyde formed is absorbed in water.

$$2CH_3OH + O_2 = 2HCHO + 2H_2O$$

When a solution of formaldehyde is evaporated, a white residue of its polymer (paraformaldehyde) is obtained. Other polymers may also be prepared.

In common with the first members of other homologous series formaldehyde has some properties which differ from those characteristic of the higher members, e.g. it does not react with ammonia like the other aldehydes but forms hexamethylenetetramine (hexamine).

$$6HCHO + 4NH_3 = \underset{\text{Hexamine}}{(CH_2)_6N_4} + 6H_2O$$

This reaction proceeds very readily, and if an ammonium salt is mixed with formaldehyde, hexamine is formed, the acid originally combined with the ammonia being liberated.

$$6HCHO + 4NH_4Cl = N_4(CH_2)_6 + 6H_2O + 4HCl$$

This reaction can be used for the assay of ammonium salts. The reverse reaction to the formation of hexamine can be effected by boiling for several hours with dilute sulphuric acid.

Formaldehyde also undergoes a change with alkali which is more characteristic of aromatic aldehydes (p. 518) than the aldehydes which belong to the aliphatic series. It is converted into an equal proportion of methyl alcohol and formic acid by simultaneous oxidation and reduction.

$$NaOH + 2HCHO = CH_3OH + HCOONa$$

Many of the synthetic "plastics" materials originate in the reactivity of formaldehyde, e.g. "bakelite" is the result of a high-pressure reaction of formaldehyde with phenol in presence of a catalyst. Similarly, other plastics start from a reaction of formaldehyde with urea.

### ASSAY OF SOLUTION OF FORMALDEHYDE

Formaldehyde is assayed by oxidation with hydrogen peroxide to formic acid.

$$H_2O_2 + HCHO = HCOOH + H_2O$$

The acid formed is determined by reaction with alkali. Hydrogen peroxide and an excess of standard alkali are added to the Solution of Formaldehyde, the excess hydrogen peroxide is decomposed by boiling, and the alkali remaining after neutralizing the formic acid is determined by titration with standard sulphuric acid. To allow for the acidity of the hydrogen peroxide solution (cf. p. 150) a blank experiment is carried out omitting the Solution of Formaldehyde.

## Acetaldehyde

Acetaldehyde is prepared on a large scale from acetylene by a process which forms the basis for the commercial preparation of many organic substances [e.g. acetic acid (p. 387), acetone (p. 381), ethyl acetate (p. 398), lactic acid (p. 407), etc.].

Acetylene is passed into warm dilute sulphuric acid in the presence of a mercuric salt as a catalyst. A series of reactions take place, the final result of which is the addition of a molecule of water to the acetylene molecule, and acetaldehyde is formed. The process is usually arranged to be continuous, the acetaldehyde vapour being removed and condensed as fast as it is formed.

$$\mathrm{CH \quad CH + H_2SO_4 \rightarrow CH_2{-}CHHSO_4}$$
$$\mathrm{CH_2 \quad CHHSO_4 + H_2SO_4 \rightarrow CH_3.CH(HSO_4)_2}$$
$$\mathrm{CH_3.CH(HSO_4)_2 + 2H_2O \rightarrow CH_3.CH(OH)_2 + 2H_2SO_4}$$
$$\mathrm{CH_3.CH(OH)_2 \rightarrow CH_3.CHO + H_2O}$$

## Paraldehyde

Paraldehyde is a colourless liquid (b.p. 126°C, cf acetaldehyde b.p. 23°C). The official substance is permitted to contain not more than 0·01 per cent of a suitable antioxidant. The presence of unpolymerized acetaldehyde can be detected by reaction with hydroxylamine hydrochloride. Paraldehyde does not react with this reagent as it contains no carbonyl group.

Paraldehyde is converted back to acetaldehyde by warming with aqueous acid or alkaline solutions. It absorbs oxygen, forming a peroxide, in keeping with its constitution as an ether (cf. formula on p. 374).

## Chloral Hydrate

Chloral is trichloracetaldehyde ($\mathrm{CCl_3.CHO}$), which forms with water chloral hydrate [$\mathrm{CCl_3.CH(OH)_2}$]. Chloral is prepared by the action of chlorine on alcohol. (It is an intermediate product in the preparation of chloroform from alcohol.) The alcohol is first oxidized by the chlorine to acetaldehyde, which is then substituted to form chloral.

Chloral hydrate is very soluble in water, but on the addition of alkalis it is decomposed into chloroform and formic acid. This reaction is the basis of the official method of assay of Chloral Hydrate.

$$\overset{\text{H ONa}}{CCl_3CHO} = CHCl_3 + \underset{\text{Sodium formate}}{HCOONa}$$

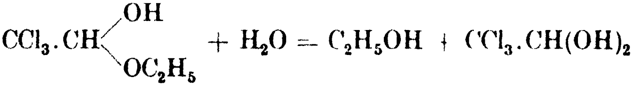
$$CCl_3.CHO + NaOH = CHCl_3 + HCOONa$$

Simultaneously part of the chloroform itself reacts.

$$CHCl_3 + 4NaOH = 3NaCl + HCOONa + 2H_2O$$

The alkali reacting in this way can be allowed for by silver nitrate titration, since three equivalents of sodium chloride are formed for every four equivalents of alkali reacting on the chloroform, i.e. 1 mil of N alkali reacting = 30/4 = 15/2 mil of N/10 silver nitrate reacting.

Chloral alcoholate $\left(CCl_3.CH\begin{matrix}OH\\ \\OC_2H_5\end{matrix}\right)$ is formed as an intermediate product in the manufacture of chloral hydrate. Its presence as an impurity in Chloral Hydrate is detected officially by hydrolysis. The alcohol formed is detected by the iodoform reaction (p. 346). The hydrolysis is carried out in alkaline solution, and the chloroform arising from the action of the alkali on the chloral is removed before testing for alcohol.



$$CCl_3.CH\begin{matrix}OH\\ \\OC_2H_5\end{matrix} + H_2O = C_2H_5OH + CCl_3.CH(OH)_2$$

*Bromal* ($CBr_3.CHO$) is obtained by a similar process to that used for chloral.

## THE ALIPHATIC KETONES

The ketones contain the carbonyl group C=O attached to two hydrocarbon radicals, which may or may not be the same, thus

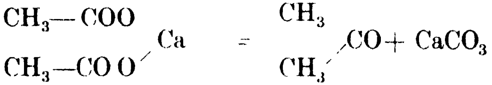
$$\underset{\substack{\text{Dimethyl ketone}\\\text{(acetone)}}}{CH_3—CO—CH_3} \qquad \underset{\text{Methyl ethyl ketone}}{CH_3—CO—C_2H_5}$$

## General Methods of Preparation of Ketones

(1) Ketones are prepared by the oxidation of the corresponding secondary alcohol, e.g. isopropyl alcohol is oxidized to acetone.

$$(CH_3)_2CHOH + O = (CH_3)_2CO + H_2O$$

(2) When the calcium salt of an organic acid is heated it decomposes and a ketone is formed.



$$\begin{matrix} CH_3\text{—}COO \\ CH_3\text{—}COO \end{matrix}\!\!>\!Ca = \begin{matrix} CH_3 \\ CH_3 \end{matrix}\!\!>\!CO + CaCO_3$$

Calcium acetate  Acetone

[In some cases the ketone may be obtained directly from the acid by heating it in contact with a suitable catalyst (thorium oxide).

$$2CH_3.COOH = (CH_3)_2CO + H_2O + CO_2.]$$

If a mixture of calcium salts of two different acids is heated, a ketone is obtained containing two different radicals attached to the carbonyl group (mixed ketone).

$$(CH_3.COO)_2Ca + (C_2H_5.COO)_2Ca = 2CH_3.CO.C_2H_5 + 2CaCO_3$$

Calcium acetate  Calcium propionate  Methyl ethyl ketone

As a special case of this latter reaction, if the calcium salt of an acid is mixed with calcium formate and heated, an aldehyde is obtained.

$$(CH_3.COO)_2Ca + (HCOO)_2Ca = 2CH_3.CHO + 2CaCO_3$$

(3) Ketones can be prepared from the magnesium alkyl halides (p. 475), and from aceto-acetic ester and its derivatives (p. 472).

## General Properties of Ketones

The properties of ketones have been indicated in connexion with those of the aldehydes and only a brief summary is necessary.

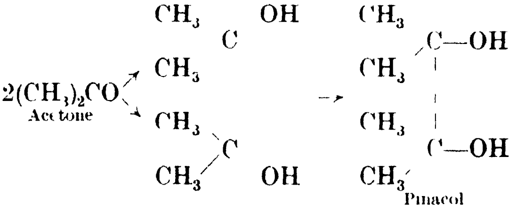
(1) Unlike aldehydes, ketones are not readily oxidized, and consequently do not reduce ammoniacal silver nitrate or

Fehling's solutions. When they are oxidized the molecule is broken down into smaller fragments, e.g. acetone is oxidized to acetic acid.

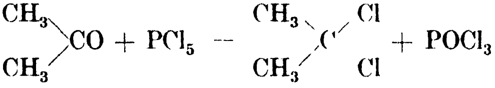
$$CH_3.CO.CH_3 + 2O_2 = CH_3.COOH + CO_2 + H_2O$$

(2) Ketones on reduction usually give the corresponding secondary alcohol, but by reduction with sodium amalgam it is possible to obtain intermediate compounds called *pinacols*, in which only one atom of hydrogen is added to the ketone molecule, and the group thus obtained is united to a similar group.

$$CH_3.CO.CH_3 + H_2 = CH_3.CH(OH).CH_3$$

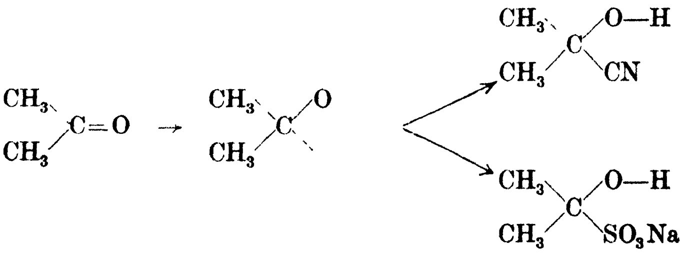


(3) Phosphorus pentachloride reacts replacing the oxygen atom by two atoms of chlorine.

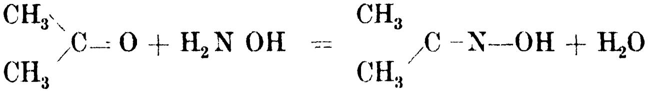


$$(CH_3)_2CO + PCl_5 = (CH_3)_2CCl_2 + POCl_3$$

(4) Ketones form addition compounds with sodium bisulphite and hydrogen cyanide, but not with ammonia.



(5) Ketones undergo condensation reactions with hydroxylamine, hydrazine, and phenylhydrazine.



$$\begin{matrix} CH_3 \\ CH_3 \end{matrix} \!\!> C = O + H_2N\,OH = \begin{matrix} CH_3 \\ CH_3 \end{matrix} \!\!> C = N - OH + H_2O$$

Acetoxime

$$(CH_3)_2C = O + H_2N.NHC_6H_5$$
$$= (CH_3)_2C = N - NHC_6H_5 + H_2O$$

Acetone phenylhydrazone

(6) Unlike the aldehydes, ketones do not polymerize.

(7) Ketones do not normally give acetals.

(8) Ketones react with magnesium alkyl halides (p. 475).

## Acetone

The most important ketone is dimethyl ketone or acetone. It is one of the substances present in the aqueous liquor obtained from the destructive distillation of wood. After the acetic acid has been separated as calcium acetate (p. 387), the acetone is separated from the methyl alcohol by distillation. Further quantities of acetone can be obtained from calcium acetate prepared from pyroligneous acid.

Acetone is also obtained by fermentation of starch by certain bacilli, and from acetaldehyde. The acetaldehyde is oxidized to acetic acid which is converted to acetone by passing over a heated catalyst (thoria). Ethyl acetate also yields acetone under these conditions.

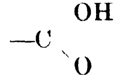
$$2CH_3.COOH = (CH_3)_2CO + H_2O + CO_2$$
$$2CH_3.COOC_2H_5 = (CH_3)_2CO + (C_2H_5)_2O + CO_2$$

Acetone reacts with cold alkaline solutions of iodine to give iodoform (cf. p. 346), and its presence in methyl alcohol may be detected by this reaction.

# CHAPTER XXIV

# THE ORGANIC ACIDS AND THEIR DERIVATIVES

## THE ALIPHATIC ACIDS

THE aliphatic acids contain the group  $—C\begin{matrix}OH\\O\end{matrix}$ usually written COOH. The glyceryl esters of the higher members of the series of the simple aliphatic acids are the *fats*. The acids are therefore often called the *fatty acids*.

The simplest members of the series are formic acid (H.COOH), acetic acid ($CH_3.COOH$), propionic acid ($C_2H_5.COOH$), butyric acid ($C_3H_7.COOH$), and valeric acid ($C_4H_9.COOH$). Other important members of the homologous series are palmitic acid ($C_{15}H_{31}.COOH$) and stearic acid ($C_{17}H_{35}.COOH$), which occur together with oleic acid (an unsaturated acid $C_{17}H_{33}.COOH$) in the naturally occurring fats.

### General Methods of Preparation of the Fatty Acids

Many acids are obtained directly from their naturally occurring salts, while others occur naturally in the form of their esters, from which they are obtained by hydrolysis. The hydrolysis of fats is used to prepare the higher fatty acids.

Synthetically acids may be prepared by the following methods—

(1) By oxidation of the corresponding alcohol or aldehyde.

(2) By hydrolysis of the cyanide. The hydrolysis may be carried out by heating with acid or alkali (p. 435).

$$RC{\equiv}N + 2H_2O = RCOOH + NH_3$$

(3) Acids are formed by the hydrolysis of aceto-acetic or malonic esters or their derivatives (p. 473).

(4) Acids may be prepared from the magnesium alkyl halides (p. 474).

(5) Acids can also be obtained by the hydrolysis of halides of the type $RCX_3$ (cf. p. 522)

$$RCX_3 \rightarrow RC(OH)_3 \rightarrow RCOOH$$

### Physical Properties of the Fatty Acids

The lower members of the series are corrosive liquids with characteristic smells. They dissolve readily in water, but the solubility decreases with increase in molecular weight, and the higher solid members are practically insoluble in water. The melting points of the acids do not rise continuously, but show a series of alternations. The melting points of the acids containing an even number of carbon atoms lie below those of the neighbouring acids containing an odd number as shown in the following table. The alternations arise from different methods of arranging the molecular chains in forming the crystals of the solid.

TABLE X

| Substance | Formula | Melting Point | Boiling Point |
|---|---|---|---|
| | | (°C) | (°C) |
| Formic acid | $H.COOH$ | 8·3 | 101 |
| Acetic acid | $CH_3.COOH$ | 16·7 | 118 |
| Propionic acid | $C_2H_5.COOH$ | − 22 | 141 |
| Butyric acid | $C_3H_7.COOH$ | − 3 | 162 |
| Valeric acid | $C_4H_9.COOH$ | − 58 | 186 |
| Caproic acid | $C_5H_{11}.COOH$ | − 1 | 205 |
| Heptoic acid | $C_6H_{13}.COOH$ | − 10 | 224 |
| Caprylic acid | $C_7H_{15}.COOH$ | 16 | 236 |
| Nonylic acid | $C_8H_{17}.COOH$ | 12 | 254 |
| Capric acid | $C_9H_{19}.COOH$ | 31 | 269 |
| Undecylic acid | $C_{10}H_{21}.COOH$ | 29 | |
| Lauric acid | $C_{11}H_{23}.COOH$ | 48 | |
| Tridecylic acid | $C_{12}H_{25}.COOH$ | 51 | |
| Myristic acid | $C_{13}H_{27}.COOH$ | 58 | |
| Pentadecylic acid | $C_{14}H_{29}.COOH$ | 54 | |
| Palmitic acid | $C_{15}H_{31}.COOH$ | 63 | |
| Margaric acid | $C_{16}H_{33}.COOH$ | 60 | |
| Stearic acid | $C_{17}H_{35}.COOH$ | 69 | |
| Nondecylic acid | $C_{18}H_{37}.COOH$ | 66 | |
| Arachidic acid | $C_{19}H_{39}.COOH$ | 75 | |
| Behenic acid | $C_{21}H_{43}.COOH$ | 83 | |
| Cerotic acid | $C_{25}H_{51}.COOH$ | 78 | |
| Melissic acid | $C_{29}H_{59}.COOH$ | 90 | |

## Chemical Properties of the Fatty Acids

With the exception of formic acid, the fatty acids are resistant to oxidation. The following reactions are typical of these acids.

(1) The hydrogen atom of the carboxyl group is acidic, and can be replaced by metals to form salts. The fatty acids

possess the usual properties of weak acids. They can be determined by direct titration with standard alkalis using phenolphthalein as indicator. (With water-insoluble acids such as are present in fat the determination can be carried out in solutions containing alcohol.)

$$CH_3.COOH + NaOH = \underset{\text{Sodium acetate}}{CH_3.COONa} + H_2O$$

(2) The acids react with alcohols to form esters, in which the hydrogen atom of the acid has been replaced by an alkyl group.

$$CH_3.COOH + C_2H_5OH = \underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5} + H_2O$$

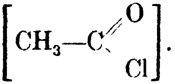
(3) The hydroxyl group of the carboxyl radical can be replaced by a chlorine atom by reaction with phosphorus chlorides.

$$3CH_3.COOH + PCl_3 = \underset{\text{Acetyl chloride}}{3CH_3.COCl} + H_3PO_3$$

$$CH_3.COOH + PCl_5 = CH_3.COCl + POCl_3 + HCl$$

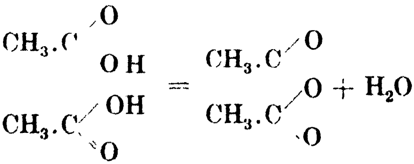
The substances formed by the replacement of the hydroxyl group by a chlorine atom are called the *acid chlorides* (cf. p. 392).

The radicals formed by the removal of the hydroxyl group from the fatty acids are called *acyl* groups. Their particular names are derived from those of the corresponding acid by altering the suffix *-ic* to *-yl*, thus acet*ic* acid $CH_3.COOH$, acet*yl* radical $(CH_3.CO)$—acet*yl* chloride $CH_3.COCl$,



$$\left[CH_3{-}C\begin{matrix}{}^{\nearrow}O\\ \searrow Cl\end{matrix}\right].$$

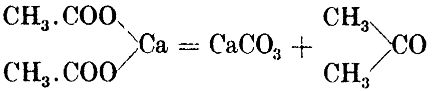
(4) The acids form anhydrides.



$$\begin{matrix}CH_3.C\begin{matrix}{}^{\nearrow}O\\ OH\end{matrix}\\ CH_3.C\begin{matrix}{}^{\nearrow}OH\\ \searrow O\end{matrix}\end{matrix} = \begin{matrix}CH_3.C\,{}^{\nearrow}O\\ \qquad\qquad {}^{\nearrow}O\\ CH_3.C\,{}^{\nearrow}\\ \qquad\quad \searrow O\end{matrix} + H_2O$$

Acetic anhydride

(5) This reaction and those following are given by certain salts of the acids. The calcium salt on heating breaks down to form a ketone.

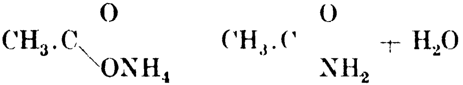


$$\begin{matrix}CH_3.COO \\ CH_3.COO\end{matrix}\!>\!Ca = CaCO_3 + \begin{matrix}CH_3 \\ CH_3\end{matrix}\!>\!CO$$

(6) The sodium salt when mixed with soda-lime and heated forms the hydrocarbon.

$$CH_3.COONa + NaOH \ - \ CH_4 + Na_2CO_3$$

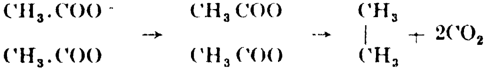
(7) The ammonium salt on heating loses water and is converted to an *acid amide* (p. 436) in which the hydroxyl group of the acid has been replaced by an amino ($NH_2$) group.



$$CH_3.C\begin{matrix}O \\ \\ ONH_4\end{matrix} \qquad CH_3.C\begin{matrix}O \\ \\ NH_2\end{matrix} + H_2O$$

Acetamide

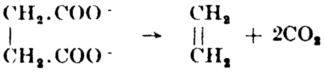
(8) When a solution of an alkali metal salt of a fatty acid is electrolyzed, a mixture of carbon dioxide and a paraffin hydrocarbon is obtained. This method of preparation of hydrocarbons is often called *Kolbe's* synthesis.



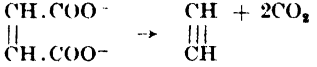
$$\begin{matrix}CH_3.COO^- \\ CH_3.COO\end{matrix} \rightarrow \begin{matrix}CH_3COO \\ CH_3COO\end{matrix} \rightarrow \begin{matrix}CH_3 \\ | \\ CH_3\end{matrix} + 2CO_2$$

Ethane

Under similar conditions, the salts of certain dibasic acids and unsaturated dibasic acids form ethylenic and acetylenic hydrocarbons respectively.



$$\begin{matrix}CH_2.COO^- \\ | \\ CH_2.COO^-\end{matrix} \rightarrow \begin{matrix}CH_2 \\ \| \\ CH_2\end{matrix} + 2CO_2$$



$$\begin{matrix}CH.COO^- \\ \| \\ CH.COO^-\end{matrix} \rightarrow \begin{matrix}CH \\ ||| \\ CH\end{matrix} + 2CO_2$$

## Formic Acid

Formic Acid occurs naturally, e.g. in ants and stinging nettles. It can be prepared by the general methods of preparation of the fatty acids, but normally it is obtained in the laboratory by heating oxalic acid with glycerol (p. 364).

$$H_2C_2O_4 = HCOOH + CO_2$$

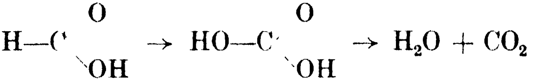
It is manufactured by heating sodium hydroxide with carbon monoxide under pressure. Combination occurs to form sodium formate, from which the acid may be obtained by distillation with sodium hydrogen sulphate.

$$NaOH + CO = HCOONa$$
$$HCOONa + NaHSO_4 = HCOOH + Na_2SO_4$$

From aqueous solutions the pure acid may be obtained by forming the lead salt, and, after drying, treating it with hydrogen sulphide.

$$PbO + 2HCOOH = (HCOO)_2Pb + H_2O$$
$$(HCOO)_2Pb + H_2S = 2HCOOH + PbS$$

Formic acid, like the lowest members of other homologous series, possesses certain abnormal properties. It is easily oxidized (for it can be regarded as an aldehyde) and is a reducing agent.



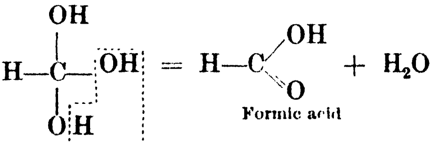
$$\mathrm{H{-}C}\begin{matrix}\mathrm{O}\\ \diagdown\mathrm{OH}\end{matrix} \rightarrow \mathrm{HO{-}C}\begin{matrix}\mathrm{O}\\ \diagdown\mathrm{OH}\end{matrix} \rightarrow H_2O + CO_2$$

Formic acid Carbonic acid

Formic acid when treated with a dehydrating agent forms carbon monoxide, which is often conveniently prepared in the laboratory by heating sodium formate and concentrated sulphuric acid.

$$HCOOH = CO + H_2O$$

Orthoformic acid [$HC(OH)_3$] is very unstable and does not exist in the free state, but the ethyl ester of this acid can be obtained by reacting on chloroform with sodium ethoxide.



Orthoformic acid

Formic acid

$$CHCl_3 + 3C_2H_5ONa = 3NaCl + \underset{\text{Ethyl orthoformate}}{CH(OC_2H_5)_3}$$

## Acetic Acid

Acetic acid is obtained on a large scale from three sources—

(1) By the oxidation of alcohol by air under the influence of certain bacteria (*Bacterium aceti*), which gives rise to a dilute solution of acetic acid (vinegar).

(2) A more concentrated solution is obtained by the destructive distillation of wood. The aqueous liquor obtained from this distillation contains acetic acid, methyl alcohol, and acetone, and it is called *pyroligneous acid*. The acetic acid may be obtained from this liquor by neutralization with milk of lime followed by separation of the methyl alcohol and acetone by distillation. The calcium acetate is converted into acetic acid by distillation with sulphuric acid. The homologues of acetic acid (present in small quantities in the pyroligneous acid) distil after the acetic acid has been collected.

$$(CH_3.COO)_2Ca + H_2SO_4 = CaSO_4 + 2CH_3.COOH$$

It is possible to separate the acetic acid from pyroligneous acid without preliminary neutralization, e.g. by scrubbing with an oil in which acetic acid dissolves preferentially, leaving the methyl alcohol and acetone in the watery liquid. The acetic acid may be recovered from the oil by distillation *in vacuo*.

(3) The third source of acetic acid is the acetaldehyde obtained from acetylene. The acetaldehyde may be oxidized by passing acetaldehyde vapour mixed with air over a heated catalyst.

### PROPERTIES OF ACETIC ACID

Acetic acid when anhydrous melts at 16·6°C and boils at 118°C. It mixes with water in all proportions. It forms well-defined salts (the acetates), most of which are soluble in water.

When chlorine is passed into hot acetic acid (especially in the presence of a catalyst, such as red phosphorus) the methyl group becomes substituted. The first product is chloracetic acid (monochloracetic acid), but on passing in the gas for a longer period or by working at higher temperatures dichloracetic and trichloracetic acids are obtained. [These substitutions indicate the presence of three hydrogen atoms in acetic acid as well as the one hydroxyl hydrogen atom indicated by the reactions with sodium and with phosphorus chlorides. The formula $CH_3.COOH$ is thus established.]

*Acetic Acid B.P.* is tested for the presence of aldehydes by their reducing action on mercuric chloride and for other oxidizable impurities (including formic acid) by reaction with potassium permanganate and dichromate. The latter test is carried out by adding the stipulated quantity of dichromate solution, and after standing, testing for excess dichromate by adding potassium iodide. If the sample conforms to requirements, iodine is liberated immediately.

*Potassium Acetate B.P.* is formed by neutralizing acetic acid with potassium carbonate. The product is dehydrated by heating until fused. It is assayed by a method which is used for certain other organic salts. This depends on the fact that organic salts of the alkali metals carbonize on heating. Various volatile products are obtained but the whole of the metal present remains in the form of the carbonate. The carbonate remaining after ignition is determined by dissolving in excess standard acid and titrating the excess with standard alkali.

$$2CH_3.COOK \rightarrow K_2CO_3$$

*Sodium Acetate* can be prepared by direct neutralization of acetic acid with sodium hydroxide or carbonate, or from the crude calcium salt by treatment with sodium sulphate. (In the latter case it is purified by recrystallization from water.) It is used officially for the preparation of Theophylline and Sodium Acetate.

*Ammonium Acetate* is official in the form of its aqueous solutions, which are prepared by direct neutralization of acetic acid with ammonia and ammonium bicarbonate.

Solution of Ammonium Acetate is assayed by the formaldehyde method (p. 376). A neutralized solution of formaldehyde is added, and the liberated acetic acid is titrated with standard sodium hydroxide solution.

$$CH_3.COONH_4 = CH_3.COOH + NH_3$$

Ammonium acetate solution should be kept in lead-free glass containers owing to its solvent action on lead silicate.

*Lead Acetate* [$(CH_3.COO)_2Pb, 3H_2O$, p. 266] is prepared by the neutralization of acetic acid by lead monoxide. In addition to its medicinal uses, it is used in dyeing and in the manufacture of white lead.

*Copper Acetate* [$(CH_3.COO)_2Cu, H_2O$] is used in certain solutions for the detection of reducing substances, especially reducing sugars.

*Butyric Acid* occurs as its glyceryl ester in butter-fat. It is formed under certain conditions by the fermentation of sugars.

*Isovaleric Acid* ($(CH_3)_2CH.CH_2.COOH$) occurs as esters in oil of valerian.

## The Higher Fatty Acids and the Soaps

The most important of the higher members of the series of fatty acids are those which occur naturally in the form of their glyceryl esters in oils and fats of animal and vegetable origin.

(The waxes are also esters of these acids with the higher monohydric alcohols, e.g. cetyl alcohol $C_{16}H_{33}OH$.)

The fatty acids can be obtained from fats by hydrolysis with steam or water under pressure.

$$\text{Fat} + \text{water} \quad \text{glycerol} + \text{fatty acid}$$

The product obtained is a semi-solid mass, the important constituents of which are palmitic acid ($C_{15}H_{31}.COOH$, m.p. 63 °C), stearic acid ($C_{17}H_{35}.COOH$, m.p. 69 °C), and the liquid oleic acid ($C_{17}H_{33}.COOH$, m.p. 14 °C). The first two acids are saturated acids containing unbranched chains of carbon atoms,

$$CH_3.CH_2.CH_2\ldots CH_2.CH_2.COOH$$

while oleic acid is an unsaturated acid containing a double bond situated in the middle of the chain of carbon atoms.

$$CH_3\,.\,(CH_2)_7.CH{=}CH.(CH_2)_7.COOH$$

The oleic acid can be separated by pressure from the solid acids, large quantities of which are used in the manufacture of candles.

The sodium and potassium salts of these acids constitute the *soaps*. Soaps are manufactured by the action of hot caustic alkali on fats. After heating the fat and caustic soda for some time, the fat becomes completely dissolved in the form of soap. This reaction is a particular example of the general action of caustic alkalis on esters (p. 395).

$$\textbf{Fat} + \textbf{sodium hydroxide} = \textbf{soap} + \textbf{glycerol}$$

The soap is separated from the solution by *salting out.* The addition of salt diminishes the solubility of the soap which rises to the surface, where it is scraped off, boiled with a little water, again separated, cut into shape, and dried. The liquor remaining after the soap has been removed contains the glycerol.

*Curd Soap* (animal soap), which is obtained from animal fats, consists chiefly of sodium stearate and palmitate. *Hard Soap* is prepared from vegetable oils and consists mainly of sodium oleate. *Soft Soap* consists of potassium oleate, which is too soluble to be precipitated from solution. The glycerol is not separated from this product. Soft Soap B.P. should contain not less than 44 per cent of fatty acids, as determined by acidifying, extracting in ether, and weighing.

The *Detergent Action of Soap* is often ascribed to the free alkali liberated by hydrolysis when the soap is dissolved in water.

$$C_{17}H_{35}.COONa + H_2O = C_{17}H_{35}.COOH + NaOH$$

There is, however, no appreciable hydrolysis when soap is dissolved in water. The detergent action is more likely due to the special nature of the soap molecule, which contains a long paraffin chain (insoluble in water, soluble in organic solvents, and non-ionic in nature) united to an end-group which is the salt of an acid and therefore tends to dissolve in water. The soap molecules can form a thin film around grease, dirt, etc., when the hydrocarbon chain will be attracted inwards towards the grease while the outer layer in contact with the water will be the carboxylic salt group. In this way the grease particle is able to be dispersed into a suspension in water (Fig. 27 (*a*). (The mechanism of formation of an emulsion of oil in water by means of soap (p. 87) is similar.)

That the detergent properties of soap are due to the presence of two groups of mutually opposing solubilities is verified by the preparation of other bodies containing a long paraffin chain and a highly water-attracting salt-like group. These bodies, such as sodium lauryl sulphate [$CH_3(CH_2)_{11}OSO_2ONa$] and cetyltrimethylammonium bromide [$(CH_3.(CH_2)_{14}.N(CH_3)_3Br)$], have similar detergent and emulsifying properties to those of ordinary soaps, and are used as substitutes thereof. It will be seen that detergency may result from the chemical presence of a cation, as well as of an anion as in soap itself.

Soap-like properties are not a general characteristic of the salts of the lower fatty acids such as sodium acetate, but only begin to appear as the chain length increases. They are first apparent about $C_9$. The explanation of this can be sought in the fact that there is a certain amount of lateral adhesion between the carbon chains of neighbouring molecules when they are arranged parallel to one another as in Fig. 27. The magnitude of this adhesion increases rapidly as the chain-length increases, but it only reaches a magnitude such that a strong, coherent and not easily destroyed film can be formed around a foreign particle when the chain contains more than 9 carbon atoms.

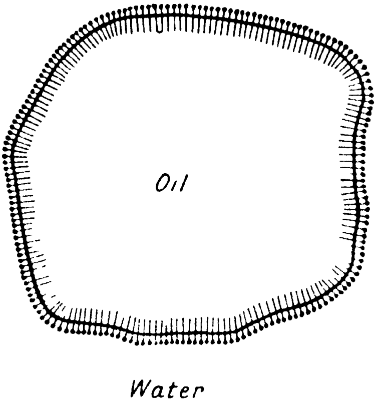


FIG. 27(*a*). DETERGENT ACTION OF SOAP

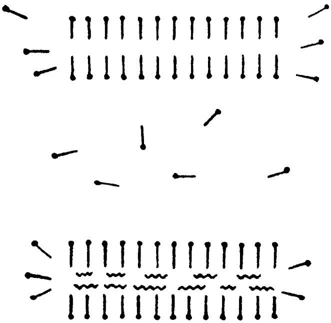


FIG. 27(*b*) SOLUBILIZATION OF OIL SOLUBLE SUBSTANCES IN THE SOAP MICELLE

The soap molecules, in consequence of this adhesion, do not exist as single molecules in solutions of ordinary concentration but as large groups called "micelles" (cf. Fig. 27 (*b*), upper part). In such groups, the hydrocarbon parts of the molecules are all together in the interior of the micelle, which can thus be regarded as a local concentration of a hydrocarbon. Thus substances such as cresol, which are soluble in hydrocarbons but not very soluble in water, dissolve readily in aqueous soap solution; actually the substance is really dissolved into the interior of the soap micelles (Fig. 27 (*b*), lower part).

### INSOLUBLE SOAPS

The term soap is applied to the insoluble lead, zinc, calcium, and barium salts of the fatty acids as well as to their sodium and potassium salts. These insoluble salts can be made either by direct neutralization of the acid with the corresponding base, or by precipitation reactions. Such reactions take place when ordinary soap is added to a hard water containing dissolved calcium and magnesium salts. The soap is completely removed from solution as the insoluble calcium or magnesium salt.

$$2NaP + CaCl_2 = 2NaCl + CaP_2$$

*Zinc Stearate* (p. 276) is prepared by double decomposition between crude sodium stearate and a soluble zinc salt. The insoluble zinc stearate is precipitated. It contains also zinc palmitate derived from sodium palmitate present in the stearate.

Soaps of other metals are present in certain official preparations, e.g. Oleated Mercury contains mercuric oleate.

## THE ACID CHLORIDES

The acid chlorides are formed by the replacement of the hydroxyl group of a fatty acid by a chlorine atom. The replacement is carried out by the interaction of a phosphorus chloride or thionyl chloride with the acid or its sodium salt.

$$PCl_3 + 3CH_3.COOH = H_3PO_3 + \underset{\text{Acetyl chloride}}{3CH_3.COCl}$$

$$SOCl_2 + 2CH_3.COOH = H_2SO_3 + 2CH_3.COCl$$

The lower members of the series are fuming liquids with an irritating smell. The higher members are solids.

### Reactions of Acid Chlorides

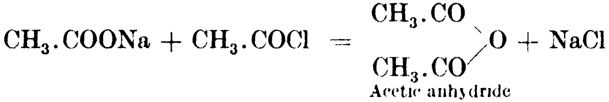
(1) Acid chlorides are easily hydrolyzed by water to form the acids.

$$CH_3.COCl + H_2O = CH_3.COOH + HCl$$

(2) They react with alcohols replacing hydrogen by the acyl group and form esters.

$$CH_3.COCl + C_2H_5OH = \underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5} + HCl$$

(3) They react with sodium salts of acids replacing sodium by the acyl group and form the acid anhydrides.



$$CH_3.COONa + CH_3.COCl = \underset{\text{Acetic anhydride}}{\left.\begin{matrix}CH_3.CO\\ CH_3.CO\end{matrix}\right>O} + NaCl$$

(4) They react with ammonia and primary and secondary amines replacing hydrogen by the acyl group.

$$CH_3.COCl + NH_3 = \underset{\text{Acetamide}}{CH_3.CONH_2} + HCl$$

$$CH_3.COCl + \underset{\text{Aniline}}{C_6H_5NH_2} = \underset{\text{Acetanilide}}{C_6H_5NH.CO.CH_3} + HCl$$

(5) Acid chlorides can be reduced to aldehydes by hydrogen in presence of metallic palladium.

$$CH_3.COCl + H_2 = CH_3.CHO + HCl$$

*Acetyl Chloride* is the most important member of the series. It is obtained from acetic acid by reaction with phosphorus trichloride, sulphur monochloride, thionyl chloride, or carbonyl chloride. It is used for acetylating various alcohols and amines, e.g. cellulose (p. 467) and aniline (p. 499).

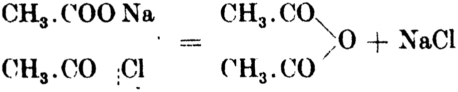
Acetyl chloride is also used to determine the number of hydroxyl groups and amino groups present in a compound, as each such group reacts with one molecule of acetyl chloride.

$$R.OH + CH_3.COCl = HCl + CH_3.COOR$$
$$R.NH_2 + CH_3.COCl = HCl + RNH.CO.CH_3$$

For the determination of the proportion of free alcohols present in volatile oils, a similar method is used to acetylate them employing acetic anhydride instead of acetyl chloride.

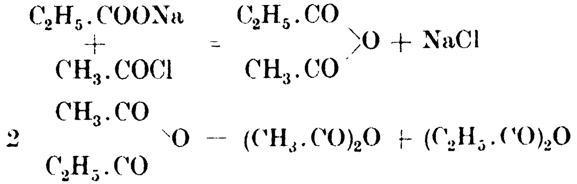
## THE ACID ANHYDRIDES

Acid anhydrides are prepared by the interaction of the sodium salt of an acid with the acid chloride.



$$\begin{matrix}CH_3.COO\,Na\\ CH_3.CO\,\vdots Cl\end{matrix} = \left.\begin{matrix}CH_3.CO\\ CH_3.CO\end{matrix}\right>O + NaCl$$

By using an acid chloride of a different acid a mixed anhydride can be obtained. On distillation mixed anhydrides break down to give a mixture of two simple anhydrides.



$$\begin{matrix} C_2H_5.COONa \\ + \\ CH_3.COCl \end{matrix} = \begin{matrix} C_2H_5.CO \\ \\ CH_3.CO \end{matrix} \rangle O + NaCl$$

$$2 \begin{matrix} CH_3.CO \\ \\ C_2H_5.CO \end{matrix} \rangle O = (CH_3.CO)_2O + (C_2H_5.CO)_2O$$

Acid anhydrides are hydrolyzed with water to form the acids. They react with alcohols and amines (to form esters and acetyl derivatives respectively) similarly to the acid chlorides. They react less vigorously than the acid chlorides but more vigorously than the acids. Acetic anhydride is often used alone or mixed with acetyl chloride in the manufacture of the acetates of cellulose and other higher hydroxylic derivatives.

## THE ESTERS

The esters are derived from the acids (organic or inorganic) by the replacement of the acidic hydrogen by an alkyl group or substituted alkyl group. Esters may be prepared —

(1) By the interaction of an acid and an alcohol. This reaction only proceeds to completion in the presence of a dehydrating agent.

(2) By the interaction of an acid chloride or anhydride and an alcohol.

(3) Esters can also be prepared by the interaction of a silver salt of the acid and an alkyl halide.

$$CH_3.COOAg + C_2H_5I = AgI + \underset{\text{Ethyl acetate}}{CH_3.COOC_2H_5}$$

### Properties of the Esters

The esters are usually volatile liquids, insoluble in water but soluble in organic solvents. Esters commonly have characteristic pleasant odours and the smell of many volatile oils is due to their ester content. Many esters are manufactured as artificial essences, and others are manufactured for use as solvents of the esters of cellulose and other substances used in the "plastics" industry.

The esters are not very reactive and their properties are quite different from those of the salts of the acids. They take part in the following reactions. (1) The reaction of an alcohol and an acid to form an ester is reversible. The esters are partially hydrolyzed on heating with water [acids and certain enzymes (e.g. lipase) catalyse this reaction].

$$CH_3.COOC_2H_5 + H_2O \quad CH_3.COOH + C_2H_5OH$$

Alkalis cause a complete conversion of the ester into the salt of the acid.

$$CH_3.COOC_2H_5 + NaOH = CH_3.COONa + C_2H_5OH$$

This reaction is called the *saponification* of the ester, and it may be compared with the conversion of fats (esters of glycerol) to soaps by heating with caustic alkali.

(2) Some esters react with ammonia to form amides.

$$CH_3.COOC_2H_5 + NH_3 = CH_3.CONH_2 + C_2H_5OH$$

## The Esters of Inorganic Acids

The esters of the halogen acids are the alkyl halides and have rather special properties. The esters of sulphuric, nitric, and nitrous acids are also of importance.

### ESTERS OF SULPHURIC ACID

By the interaction of ethyl alcohol and sulphuric acid, at first only one atom of hydrogen is replaced by the alkyl group and *ethyl hydrogen sulphate* is obtained. It is possible to prepare *diethyl sulphate* by further reaction.

*Dimethyl Sulphate* is prepared from the corresponding methyl hydrogen sulphate by action of heat.

$$2CH_3HSO_4 \quad (CH_3)_2SO_4 + H_2SO_4$$

Dimethyl sulphate is a very poisonous substance which has an extensive use in the laboratory and in industry as a reagent. It readily reacts with alcohols replacing hydrogen by a methyl group (*methylation*).

$$C_2H_5OH + (CH_3)_2SO_4 = C_2H_5.O.CH_3 + CH_3HSO_4$$

### THE ESTERS OF NITRIC ACID

These are obtained by the action of the corresponding alcohol on a mixture of nitric and sulphuric acids. The reaction of concentrated nitric acid with ethyl alcohol is often violent, and owing to the oxidizing action of the acid, clouds of brown fumes are evolved. When the rate of reaction is controlled, a mixture of ethyl nitrate and ethyl nitrite is formed, owing to the reduction of part of the nitric acid by some of the alcohol, which is oxidized to acetaldehyde.

$$HNO_3 + C_2H_5OH = HNO_2 + CH_3.CHO + H_2O$$

Pure ethyl nitrate can be obtained by reacting in presence of urea, which removes the nitrous acid as soon as it is formed (p. 441).

*Glyceryl Trinitrate.* Glycerol contains three hydroxyl groups and therefore forms a tri-nitric ester with three molecules of nitric acid. This ester is also called nitroglycerin, although it is not a true nitro derivative.

Glyceryl trinitrate is manufactured by adding pure anhydrous glycerol with continuous stirring to a well-cooled mixture of sulphuric and nitric acids. (Care is required in the design and manipulation of the apparatus, to avoid frictional contacts likely to cause explosion.) After the reaction is complete, the liquids are run into vessels where the nitroglycerin rises to the surface and is skimmed off, washed free from acid and dried.

In the pure state nitroglycerin is too sensitive to be a reliable explosive. It is rendered more safe to handle by mixing with an inert substance such as kieselguhr (a siliceous earth) in the manufacture of dynamite, or by mixing with nitrocellulose in the manufacture of cordite and blasting gelatin.

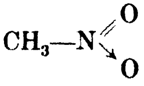
*Tablets of Glyceryl Trinitrate* are assayed by a colorimetric method depending on the nitration of phenoldisulphonic acid with production of a coloured nitro derivative (cf. p. 513).

THE ESTERS OF NITROUS ACID

The nitrous acid esters are isomeric with the nitroparaffins, but they have a different molecular structure and different properties.

$H—O—N = O$
Nitrous acid

$CH_3—O—N = O$
Methyl nitrite



$CH_3—N\genfrac{}{}{0pt}{}{\nearrow O}{\searrow O}$

Nitromethane

*Ethyl Nitrite* is formed by the reaction of nitrous acid and ethyl alcohol. It is prepared either (1) by adding sodium nitrite to a cold acidified solution of ethyl alcohol, or (2) by distilling a mixture of sulphuric and nitric acids with alcohol and copper, when an alcoholic solution of ethyl nitrite is obtained.

$$NaNO_2 + HCl + C_2H_5OH = C_2H_5NO_2 + NaCl + H_2O$$

$$Cu + HNO_3 + C_2H_5OH + H_2SO_4 = C_2H_5NO_2 + CuSO_4 + 2H_2O$$

*Spirit of Nitrous Ether* is assayed on its ethyl nitrite content. The determination depends on the reaction with potassium iodide in acid solution by which nitric oxide is liberated (p. 196). The experiment is carried out in a nitrometer charged with a solution of common salt in which nitric oxide is not very soluble. The volume of gas obtained (after correction to a standard pressure and temperature) is a measure of the ethyl nitrite content of the spirit.

$$\begin{aligned}2C_2H_5NO_2 + 2KI + H_2SO_4 \\ = I_2 + 2NO + 2C_2H_5OH + K_2SO_4\end{aligned}$$

*Amyl Nitrite* (prepared by acting with sulphuric acid on a solution of sodium nitrite and commercial amyl alcohol) is determined by a similar process.

### THE ESTERS OF CARBONIC ACID

These substances are prepared by the following reactions.

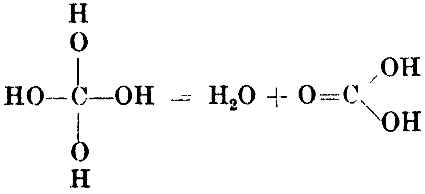
(1) By the action of the corresponding alcohol on carbonyl chloride.

$$COCl_2 + 2C_2H_5OH = \underset{\text{Ethyl carbonate}}{CO(OC_2H_5)_2} + 2HCl$$

(2) By the action of alkyl halides on silver carbonate.

$$2C_2H_5I + Ag_2CO_3 = 2AgI + (C_2H_5)_2CO_3$$

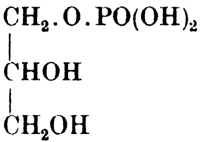
They are soluble in water, by which they are slowly hydrolyzed. Orthocarbonate esters can also be prepared, although the corresponding acid is not known in the free state.



Orthocarbonic acid

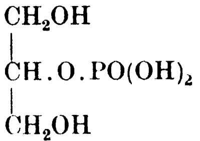
## THE GLYCERYL ESTERS OF PHOSPHORIC ACID

α and β glyceryl monophosphates are present in glycerophosphoric acid.



$$\begin{array}{l} CH_2.O.PO(OH)_2 \\ | \\ CHOH \\ | \\ CH_2OH \end{array}$$

α glyceryl monophosphate



$$\begin{array}{l} CH_2OH \\ | \\ CH.O.PO(OH)_2 \\ | \\ CH_2OH \end{array}$$

β glyceryl monophosphate

## The Esters of Organic Acids

*Ethyl Acetate* is prepared on an industrial scale for use as a solvent and in the manufacture of perfumes. A large quantity is now obtained directly from synthetic acetaldehyde by a catalytic reaction, in the presence of aluminium ethoxide $[Al(OC_2H_5)_3]$.

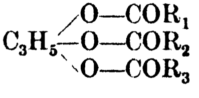
$$2CH_3.CHO = CH_3.COOC_2H_5$$

It is also prepared by reacting on ethyl alcohol with acetic acid in presence of concentrated sulphuric acid.

Many other esters are also prepared commercially for use as solvents and in the perfume industry, e.g. amyl acetate, butyl acetate, ethyl butyrate.

## The Oils, Fats, and Waxes

The fats of animal and vegetable origin are mixtures containing various proportions of the esters of glycerol with palmitic, stearic, and oleic acids. Glycerol being a trihydric alcohol, the esters are formed by combination with three molecules of the acids. The pure esters are often called *tripalmitin*, *tristearin*, and *triolein* respectively. [A similar nomenclature is sometimes used for the glyceryl esters of the other acids, e.g. triacetin (glyceryl triacetate) trinitrin (glyceryl trinitrate), monoformin (glyceryl monoformate).] Glycerides of the type in which all three hydroxyl groups are united to similar acid radicals are called *simple glycerides*. Many natural fats contain large quantities of *mixed glycerides* containing more than one acid radical, e.g.



$$C_3H_5\begin{cases} O-COR_1 \\ O-COR_2 \\ O-COR_3 \end{cases}$$

The melting points of the pure fatty esters are tripalmitin 63°C, tristearin 66°C, triolein — 6°C. The consistency of any particular oil or fat depends on the relative proportion of triolein it contains, the more liquid oils containing a high proportion.

The fats and fatty oils are extracted from the raw material by melting out, or by the influence of pressure. They may also be obtained by extraction with a suitable organic solvent. (The fats are insoluble in water, more soluble in alcohol, but readily soluble in such solvents as chloroform or benzene.)

The oils and fats behave in accordance with the reactions of esters. (1) They are hydrolyzed by treatment with steam or acids to give glycerol and the fatty acid, which is often prepared by this reaction. (2) They react with alkalis to form glycerol and salts of the acids (the soaps).

The *waxes* are esters not of glycerol but of simple monohydric alcohols containing a long carbon chain. Beeswax contains the palmitic esters of myricyl alcohol ($C_{30}H_{61}OH$) together with other alcohols and acids in the uncombined state.

Various tests are made on the oils, fats and waxes to indicate the relative proportions of the esters of palmitic, stearic and oleic acids which they contain, and the presence of other non-fatty substances.

The *Acid Value* is defined as the number of milligrammes of potassium hydroxide required to neutralize the free acid in 1 g of the substance. It is determined by dissolving in alcohol-ether and titrating with alkali, using phenolphthalein as indicator. It indicates the amount of fatty acid in the uncombined state.

The *Saponification Value* is defined as the number of milligrammes of potassium hydroxide required to neutralize the fatty acids obtained from 1 g of the oil or fat by hydrolysis, and thus includes the alkali acting on the free acids as well as that used to hydrolyze the esters. It is determined by hydrolysis with a known amount of standard alcoholic potassium hydroxide solution. After the reaction is complete, the excess alkali is found by back titration.

$$\mathrm{R.COOR_1 + KOH \qquad R.COOK + R_1OH}$$

The *Unsaponifiable Matter* consists of all those substances which do not react with alkali (e.g. hydrocarbons, alcohols).

The determination is carried out by treatment with alcoholic potash to react with the acid and esters. The unsaponifiable matter is extracted with ether, dried and weighed. The residue has to be tested for the absence of fatty acids obtained by the hydrolysis of salts during the extraction.

Similar processes are used to control the purity of esters and the ester content of volatile oils.

The *Ester Value* is defined as the number of milligrammes of potassium hydroxide required to neutralize the acids from the complete hydrolysis of 1 g of the substance. In this case, the free acid is neutralized before carrying out the quantitative saponification.

$$\mathrm{R.COOR_1 + H_2O = R.COOH + R_1OH}$$
$$\mathrm{R.COOH + KOH = R.COOK + H_2O}$$

Certain official esters (e.g. ethyl oleate) are directly assayed by the same process, which involves hydrolysis with alcoholic potash followed by back titration.

For beeswax, the ester value is calculated by subtracting the acid value from the saponification value. An additional check on the proportion of free to combined acid is introduced in the form of a "ratio number" defined as the ester value/acid value.

The *Acetyl Value* is a measure of the free alcohols present in the substance. These are converted into acetates by reaction with acetic anhydride. The acetates are separated and quantitatively saponified. The acetyl value is defined as the number of milligrammes of potassium hydroxide required to neutralize the acetic acid from 1 g of the acetylated substance.

$$\mathrm{2ROH + (CH_3.CO)_2O = 2CH_3.COOR + H_2O}$$
$$\mathrm{CH_3.COOR + H_2O = CH_3.COOH + ROH}$$
$$\mathrm{CH_3.COOH + KOH = CH_3.COOK + H_2O}$$

# CHAPTER XXV

# THE UNSATURATED, HYDROXY, AND POLYBASIC ACIDS

WHEN a compound contains more than one reactive organic group in the molecule it usually exhibits the properties of, and takes part in, the reactions characteristic of all the different groups present. It is prepared by suitable modifications of the general methods of preparation for the particular groups.

## THE UNSATURATED ACIDS

Unsaturated acids contain a double bond and a carboxyl group. The simplest acid is acrylic acid ($CH_2 = CH.COOH$, which corresponds to allyl alcohol $CH_2 = CH.CH_2OH$, and acrolein $CH_2 = CH.CHO$).

Crotonic acid ($CH_3.CH = CH.COOH$) is the next member of the series (the corresponding aldehyde being obtained from acetaldehyde). The most important member of the series is oleic acid ($CH_3.(CH_2)_7.CH = CH.(CH_2)_7.COOH$). Ricinoleic acid is a hydroxy unsaturated acid related to oleic acid ($CH_3.(CH_2)_5.CHOH.CH_2.CH = CH(CH_2)_7COOH$). Its glyceride is the chief constituent of castor oil.

The unsaturated acids possess properties characteristic of ethylenic derivatives as well as the acidic properties due to the carboxyl group. They are readily oxidized, splitting at the double bond which can thus be located. (Drying oils contain compounds of unsaturated acids, such as linoleic acid.) They combine readily with halogens, hydrogen halides, and hydrogen (in the presence of a catalyst) to form addition compounds. The proportion of olein in a fat can be determined by measurement of the quantity of iodine absorbed, for the other constituents (palmitin and stearin) being saturated do not react with iodine.

The *Iodine Value* of a fat or oil is defined as the weight of iodine absorbed by 100 parts by weight of the substance. It is determined (Wij's method) by dissolving the fat or oil in carbon tetrachloride, and adding a solution of iodine monochloride. Iodine monochloride adds on at the double bond of the molecule of olein.

After standing until the reaction is complete, the excess iodine monochloride is determined by adding potassium iodide, and titrating the liberated iodine with sodium thiosulphate.

$$ICl + KI = KCl + I_2$$

The concentration of the iodine monochloride solution is determined by a similar experiment omitting the fat. The result is expressed in terms of iodine ($ICl \equiv I_2$).

An alternative method uses instead of iodine monochloride a solution of bromine in pyridine in presence of acetic and sulphuric acids. The bromine adds on at the double bond. The experimental procedure is similar.

## The Hardening of Fats

The liquid fats and oils can be converted into solid fats if the unsaturated oleic acid esters are converted into saturated stearates. Fat hardening is an industrial process by which unsaturated fats and oils can be converted into clean and edible fats.

The conversion is carried out by the addition of hydrogen at the double bond by reacting in the presence of a nickel catalyst.

$$CH_3.(CH_2)_7.CH{=}CH.(CH_2)_7.COOH + H_2 \\ \rightarrow CH_3.(CH_2)_{16}.COOH$$

The liquid fat is allowed to trickle down over the surface of the nickel catalyst in an atmosphere of hydrogen, the saturated fat being collected as it is formed.

## Oleic Acid

The position of the double bond in oleic acid is shown by the fact that on oxidation it gives a mixture of two acids each containing 9 carbon atoms.

$$CH_3.(CH_2)_7.CH{=}CH.(CH_2)_7.COOH \\ \rightarrow CH_3.(CH_2)_7.COOH + COOH.(CH_2)_7.COOH$$

Elaidic acid is represented by the same formula as oleic acid and the two substances are geometrical isomers (p. 430).

Oleic acid is obtained by the hydrolysis of suitable fats by dilute acids or steam. It is separated by expression from the solid acids also formed. It is difficult to obtain a complete separation, and the pure acid is obtained by taking advantage of the greater solubility of lead oleate in ether compared with lead palmitate and stearate.

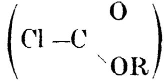
*Oleic Acid B.P.* should not contain a greater quantity of saturated acids than will cause solid to separate at a temperature above 10°C. (The melting point of pure oleic acid is 14°C but it normally only commences to solidify much below this temperature owing to supercooling.)

Oleic acid absorbs oxygen from the air and becomes darker in colour and rancid.

*Ethyl Oleate* is officially assayed by the saponification process used for other esters (p. 400).

## THE HALOGEN SUBSTITUTED ACIDS

The simplest halogen substituted acid (chloroformic acid Cl.COOH) cannot be prepared except as esters, which are obtained by the action of phosgene on alcohols and possess properties associated with acid chlorides



$$\left(Cl-C\begin{matrix}O\\ \\ OR\end{matrix}\right)$$

$$\underset{\text{Phosgene}}{ClCOCl} + HOC_2H_5 = \underset{\text{Ethyl chloroformate}}{ClCOOC_2H_5} + HCl$$

The higher halogen substituted acids are stable and, when chlorine is passed into acetic acid, substitution takes place and mono-, di-, and trichloracetic acids are obtained successively.

$$CH_3.COOH + Cl_2 = \underset{\text{Monochloracetic acid}}{CH_2Cl.COOH} + HCl$$

$$CH_2Cl.COOH + Cl_2 = \underset{\text{Dichloracetic acid}}{CHCl_2.COOH} + HCl$$

$$CHCl_2.COOH + Cl_2 = \underset{\text{Trichloracetic acid}}{CCl_3.COOH} + HCl$$

Trichloracetic acid is prepared more conveniently by the oxidation of the corresponding aldehyde (chloral) with nitric acid.

$$CCl_3.CHO + O = CCl_3.COOH$$

The strengths of these three acids increase with the number of chlorine atoms introduced into the molecule.

The chlorine atoms possess the usual properties of halogen atoms substituted in organic compounds, e.g. they may be replaced by hydroxyl and amino groups. In consequence of the reactivity of these halogen atoms, the substituted acids are important in the synthesis of many other compounds, e.g. glycollic acid or glycine, which are obtained in the form of their salts by reaction with caustic potash or ammonia.

$$CH_2Cl.COOH + KOH = \underset{\substack{\text{Glycollic acid} \\ \text{(Hydroxyacetic acid)}}}{CH_2OH.COOH} + KCl$$

$$CH_2Cl.COOH + NH_3 = \underset{\substack{\text{Glycine} \\ \text{(Amino-acetic acid)}}}{CH_2NH_2.COOH} + HCl$$

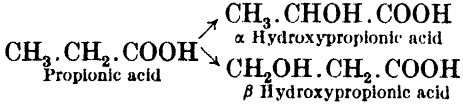
*Trichloracetic Acid* is assayed officially on its chlorine content. As the halogen atoms do not react directly with silver nitrate, the compound is first fused with sodium carbonate to destroy the organic matter and to leave the chlorine as sodium chloride. The latter substance is then determined by adding excess silver nitrate and nitric acid and back titrating with ammonium thiocyanate solution (cf. p. 121).

## THE HYDROXY ACIDS

The hydroxy acids contain in their molecule both a hydroxyl group and a carboxyl group, and, in general, exhibit the properties of an alcohol as well as an acid (e.g. lactic acid which contains a secondary alcohol grouping is oxidized to pyruvic acid).

$$CH_3.CHOH.COOH \rightarrow CH_3.CO.COOH$$

The simplest member of the series is glycollic acid (hydroxyacetic acid) ($CH_2OH.COOH$). The next members of the series are derived from propionic acid. It is possible to substitute a hydroxyl group in the propionic acid molecule in two different positions thus—



$$\underset{\text{Propionic acid}}{CH_3.CH_2.COOH} \begin{array}{l} \nearrow \underset{\alpha\ \text{Hydroxypropionic acid}}{CH_3.CHOH.COOH} \\ \searrow \underset{\beta\ \text{Hydroxypropionic acid}}{CH_2OH.CH_2.COOH} \end{array}$$

In these and similar cases, the derivatives obtained are distinguished from one another by the use of the letters α, β, γ, etc., to indicate the position of the hydroxyl or other substituted group, starting with the carbon atom next to the carboxyl group, e.g.

$$CH_3.CHOH.COOH$$

α Hydroxypropionic acid

$$CH_2OH.CH_2.COOH$$

β Hydroxypropionic acid

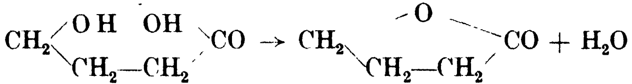
$$CH_2OH.CH_2.CH_2.COOH$$

γ Hydroxybutyric acid

α and β hydroxypropionic acids are more commonly known as lactic and hydracrylic acids respectively.

## Comparison of the Properties of Hydroxy Acids

The hydroxy acids contain in their molecules two groups (a hydroxyl and a carboxyl group) which tend to react with one another to form esters. The properties of a particular hydroxy acid depend on the relative position of these two groups in the molecule. When the two groups react together, the resultant ester-like compound has a ring structure. For example, with γ and δ hydroxy acids the union of the alcoholic and acidic groups takes place on heating, and the resultant compound is called a *lactone* (or internal anhydride).



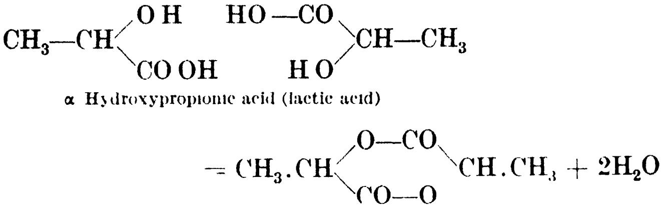
γ Hydroxybutyric acid — Butyrolactone

With the β hydroxy acids the strain produced by ring formation (cf. p. 542) renders the β lactones very unstable. Therefore such acids do not form anhydrides but instead break down on heating to form unsaturated acids.

$$CH_2OH.CH_2.COOH \rightarrow CH_2{=}CH.COOH + H_2O$$

β Hydroxypropionic acid (Hydracrylic acid) — Acrylic acid

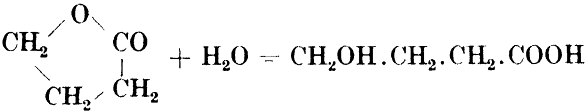
No lactones can be formed when the hydroxyl group and the carboxyl groups are immediate neighbours, but instead, esters can be formed by union together of two molecules of the α hydroxy acids, when the hydroxyl group of the one acid combines with the carboxyl group of the other. Such cyclic esters are called *lactides.*



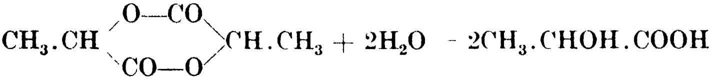
α Hydroxypropionic acid (lactic acid)

Lactide

Lactones and lactides being ester-like compounds can be hydrolyzed to reform the original hydroxy acids.



Butyrolactone



Lactide

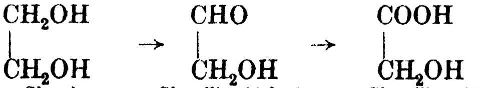
## Glycollic Acid

Glycollic acid (hydroxyacetic acid) may be prepared by the general methods—

(1) From monochloracetic acid by replacing the chlorine atom with a hydroxyl group by reaction with moist silver oxide.

$$CH_2Cl.COOH + AgOH = AgCl + CH_2OH.COOH$$

(2) By oxidation of the corresponding alcohol (glycol).



$$\begin{matrix} CH_2OH \\ | \\ CH_2OH \end{matrix} \rightarrow \begin{matrix} CHO \\ | \\ CH_2OH \end{matrix} \rightarrow \begin{matrix} COOH \\ | \\ CH_2OH \end{matrix}$$

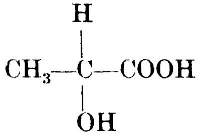
Glycol Glycollic aldehyde Glycollic acid

(3) From amino-acetic acid by reaction with nitrous acid.

### Lactic Acid

Lactic acid is α hydroxypropionic acid and contains a carbon atom united to four different radicals.

$CH_3.CHOH.COOH;$



$$CH_3-\overset{\displaystyle H}{\overset{|}{\underset{\underset{\displaystyle OH}{|}}{C}}}-COOH$$

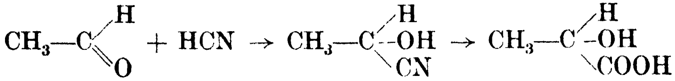
Under these circumstances, it is possible to obtain three isomeric substances, two of which have similar chemical and physical properties, but differ in their behaviour to plane polarized light, one being dextro-rotatory, the other laevo-rotatory. The third isomer is optically neutral, being the result of mixing the other two forms in equal proportions. The theoretical basis of this type of isomerism (*stereoisomerism*) is discussed later (p. 419).

Ordinary lactic acid is the inactive (or racemic) form. The dextro-rotatory acid (sarcolactic acid) occurs in meat juices and is obtainable from meat extract. The laevo-form does not occur naturally but may be obtained by removing the dextro-rotatory fraction of the inactive mixture.

Ordinary or fermentation lactic acid is formed during the souring of milk, as the result of the "lactic fermentation" of the sugars (lactose) present, by the lactic bacillus. It is manufactured from sour milk or by the lactic fermentation of sugars other than lactose (e.g. sucrose in sugar molasses and the sugars formed by the hydrolysis of wood shavings). The fermentation is carried out in presence of excess calcium carbonate to prevent the solution becoming too acid. The lactic acid is neutralized as it is formed by the calcium carbonate with the formation of insoluble calcium lactate. The lactic acid is obtained from its calcium salt by addition of dilute sulphuric acid. After filtering, the lactic acid is concentrated by evaporation *in vacuo.*

$$\begin{aligned}(CH_3.CHOH.COO)_2Ca &+ H_2SO_4\\ &= 2CH_3.CHOH.COOH + CaSO_4\end{aligned}$$

Lactic acid is also obtained by synthetic reactions. Acetaldehyde adds on hydrogen cyanide to form acetaldehyde cyanhydrin, which on hydrolysis yields lactic acid. (This series of reactions establishes the constitutional formula of lactic acid.)



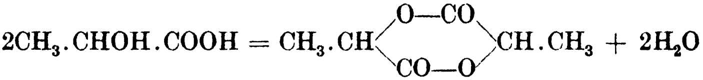
$$CH_3—C\begin{smallmatrix}H\\O\end{smallmatrix} + HCN \rightarrow CH_3—C\begin{smallmatrix}H\\OH\\CN\end{smallmatrix} \rightarrow CH_3—C\begin{smallmatrix}H\\OH\\COOH\end{smallmatrix}$$

Lactic acid may also be obtained from the corresponding α chloropropionic acid by hydrolysis, and from α aminopropionic acid by reaction with nitrous acid.

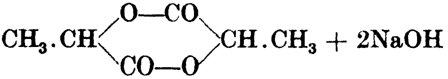
$$CH_3.CHCl.COOH + AgOH = CH_3.CHOH.COOH + AgCl$$

$$CH_3.CHNH_2.COOH + HNO_2$$
$$= CH_3.CHOH.COOH + H_2O + N_2$$

Lactic acid when free from water is a crystalline solid (m.p. 18°C), but it is very hygroscopic and as ordinarily obtained it is a syrupy viscous liquid containing 10 per cent or more of water. Lactic acid possesses the usual properties of α hydroxy acids. Lactide formation takes place fairly readily, and during the evaporation of the water in the manufacturing process of lactic acid a certain amount of lactide is formed.



In the official method of assay of Lactic Acid, the lactic acid and lactide are calculated as lactic acid. The determination is carried out by boiling with excess standard sodium hydroxide solution, which neutralizes the lactic acid, and hydrolyzes the lactide.



$$= 2CH_3.CHOH.COONa$$
Sodium lactate

After the reaction is complete, the excess alkali is titrated with standard acid. To allow for loss of alkali by reaction with the glass vessels during the boiling, a blank experiment is necessary, and this is carried out under similar conditions omitting the lactic acid.

Lactic acid on oxidation with potassium permanganate yields acetaldehyde.

$$CH_3.CHOH.COOH + O \rightarrow CH_3.CHO + CO_2 + H_2O$$

*Calcium Lactate* [ $(CH_3.CHOH.COO)_2Ca$; $5H_2O$) ] is obtained by neutralization of lactic acid with calcium carbonate. It is officially assayed on its calcium content (p. 257).

**Aldehydic and Ketonic Acids**

These acids, which contain in addition to the carboxyl group an aldehyde or ketone group, possess the properties of aldehydes or ketones as well as acids. They may be prepared by suitable modifications of the general methods. They give rise to the type of isomerism known as tautomerism or dynamic isomerism (p. 471). The more important compounds are (1) aldehydic acids, glyoxalic acid $\begin{array}{l}CHO\\|\\COOH\end{array}$ (a product of the oxidation of glycol), (2) ketonic acids, pyruvic acid ($CH_3.CO.COOH$) (an intermediate product in the fermentation of sugar) and aceto-acetic acid ($CH_3.CO.CH_2.COOH$), the ester of which is a very important synthetic reagent (p. 470).

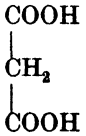
$$\begin{array}{l}CHO\\|\\COOH\end{array}$$

## THE DIBASIC ACIDS

Dibasic organic acids contain two carboxyl groups, and form a homologous series, of which oxalic acid

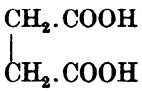
$$\begin{array}{l}COOH\\|\\COOH\end{array}$$

is the simplest member. Other important members of the series are malonic acid and succinic acid



$$\begin{array}{l}COOH\\|\\CH_2\\|\\COOH\end{array}$$

Malonic acid



$$\begin{array}{l}CH_2.COOH\\|\\CH_2.COOH\end{array}$$

Succinic acid

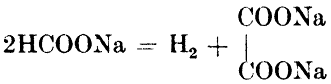
The dibasic acids occur in nature in the free state and in the form of their salts. They may be prepared synthetically by general methods, and these synthetic methods are often of importance in proving the constitutions of the particular acids.

The dibasic acids are usually crystalline solids soluble in water. They possess the usual acid properties, and being dibasic, normal and acid salts may be obtained.

## Oxalic Acid

Oxalic acid $\begin{array}{l}\mathrm{COOH}\\ |\\ \mathrm{COOH}\end{array}$ occurs widely in nature. Many plants contain the acid potassium salt ($KHC_2O_4$) in considerable quantity, some contain the calcium salt, while others contain the free acid. Oxalic acid is obtained as a product of the oxidation of many organic compounds, and in the laboratory it is often prepared by the oxidation of cane sugar with nitric acid.

Oxalic acid is manufactured from sodium formate (prepared from carbon monoxide and sodium hydroxide). On heating, the formate decomposes and sodium oxalate is obtained.



$$2HCOONa = H_2 + \begin{array}{l}\mathrm{COONa}\\ |\\ \mathrm{COONa}\end{array}$$

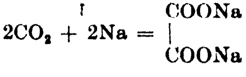
It may also be obtained from cellulose (in the form of sawdust) by fusing in the presence of air with sodium hydroxide. The sodium oxalate formed is dissolved in water, and converted into the calcium salt by adding milk of lime. (The sodium hydroxide is thus recovered.)

$$Na_2C_2O_4 + Ca(OH)_2 = CaC_2O_4 + 2NaOH$$

The precipitated calcium oxalate is filtered, and free oxalic acid is obtained from it by treatment with sulphuric acid.

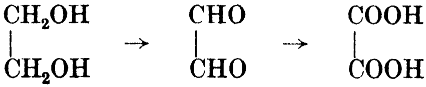
$$CaC_2O_4 + H_2SO_4 = CaSO_4 + H_2C_2O_4$$

Sodium oxalate is also obtainable by direct combination of carbon dioxide and heated sodium.

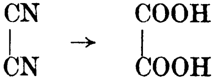


$$2CO_2 + 2Na = \begin{array}{l}\mathrm{COONa}\\ |\\ \mathrm{COONa}\end{array}$$

The constitution of oxalic acid may be established by its formation from glycol by oxidation, and from cyanogen by hydrolysis.



$$\begin{array}{l}CH_2OH\\ |\\ CH_2OH\end{array} \rightarrow \begin{array}{l}CHO\\ |\\ CHO\end{array} \rightarrow \begin{array}{l}COOH\\ |\\ COOH\end{array}$$



$$\begin{array}{l}CN\\ |\\ CN\end{array} \rightarrow \begin{array}{l}COOH\\ |\\ COOH\end{array}$$

### PROPERTIES OF OXALIC ACID

Oxalic acid crystallizes with two molecules of water of crystallization. It is a dibasic acid, and forms acid salts such as potassium binoxalate $KHC_2O_4$, and neutral salts such as potassium oxalate $K_2C_2O_4$, $2H_2O$. The salts of the alkali metals are soluble in water, but the oxalates of other metals are insoluble in water. The calcium and lead salts are sufficiently insoluble to be used to precipitate calcium or lead oxalate quantitatively from aqueous solution, and this forms the basis of certain gravimetric determinations. In addition to the acid and neutral salts, quadroxalates are known, which are formed by the combination of a molecule of oxalic acid with a molecule of the acid salt, e.g. potassium quadroxalate $KHC_2O_4$, $H_2C_2O_4$, $2H_2O$. Oxalic acid and its soluble salts are poisonous.

Oxalic acid is oxidized to carbon dioxide and water by a warm acidified solution of potassium permanganate.

$$H_2C_2O_4 + O = H_2O + 2CO_2$$

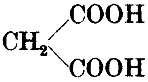
This reaction can be used as the basis of the determination of oxalic acid or of potassium permanganate, and it is also important in the official methods for the assay of certain calcium compounds.

When subjected to the action of dehydrating agents (for example, when heated with concentrated sulphuric acid) oxalic acid yields a mixture of carbon monoxide and carbon dioxide. It is used for the laboratory preparation of carbon monoxide.

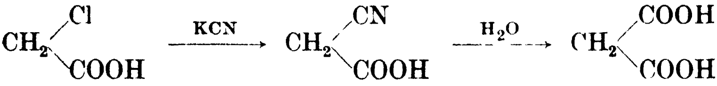
$$H_2C_2O_4 = H_2O + CO + CO_2$$

When heated with glycerol, oxalic acid breaks down into formic acid (p. 364).

## Malonic Acid

Malonic acid  $CH_2(COOH)_2$ occurs as the calcium salt in beetroot. It is prepared by the following series of reactions which serve to establish its constitution.

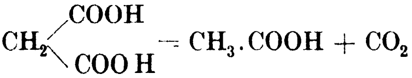
Monochloracetic acid is converted into cyanacetic acid by reaction with potassium cyanide, and cyanacetic acid on hydrolysis gives malonic acid.



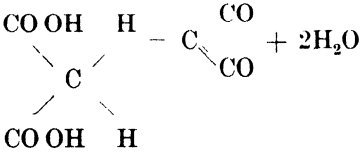
$$CH_2(Cl)COOH \xrightarrow{KCN} CH_2(CN)COOH \xrightarrow{H_2O} CH_2(COOH)_2$$

Monochloracetic acid Cyanacetic acid Malonic acid

Malonic acid when heated alone loses carbon dioxide and acetic acid is formed, but in presence of a dehydrating agent malonic anhydride (carbon suboxide $C_3O_2$) is obtained.



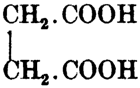
$$CH_2(COOH)_2 = CH_3.COOH + CO_2$$



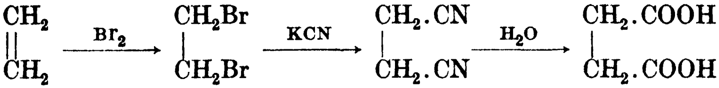
$$C(COOH)_2H_2 = C(CO)_2 + 2H_2O$$

Ethyl malonate is used as a synthetic reagent for the preparation of organic acids (p. 473).

## Succinic Acid

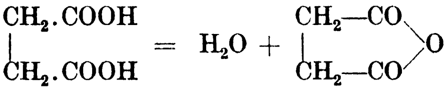
Succinic acid  $CH_2.COOH-CH_2.COOH$ occurs in many plants and animal products. It may be obtained by the distillation of amber. Its constitution is confirmed by its synthesis by the following series of reactions—

Ethylene dibromide is obtained by the addition of bromine to ethylene; it is converted to the cyanide, which on hydrolysis yields succinic acid.



$$\begin{array}{l}CH_2\\ \|\\ CH_2\end{array} \xrightarrow{Br_2} \begin{array}{l}CH_2Br\\ |\\ CH_2Br\end{array} \xrightarrow{KCN} \begin{array}{l}CH_2.CN\\ |\\ CH_2.CN\end{array} \xrightarrow{H_2O} \begin{array}{l}CH_2.COOH\\ |\\ CH_2.COOH\end{array}$$

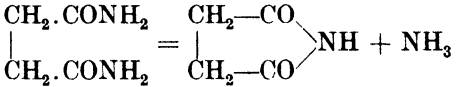
Succinic acid differs from the lower members of the series of dibasic acids as it forms an internal anhydride when heated.



$$\begin{array}{l}CH_2.COOH\\ |\\ CH_2.COOH\end{array} = H_2O + \begin{array}{l}CH_2-CO\\ |\\ CH_2-CO\end{array}\!\!>O$$

Succinic anhydride

In a similar manner succinamide forms succinimide with loss of ammonia.

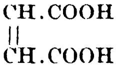


$$\begin{array}{l}CH_2.CONH_2\\ |\\ CH_2.CONH_2\end{array} = \begin{array}{l}CH_2-CO\\ |\\ CH_2-CO\end{array}\!\!>NH + NH_3$$

Succinamide Succinimide

**Unsaturated Dibasic Acids**

The most important members of the series of unsaturated dibasic acids are the isomeric maleic and fumaric acids.

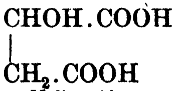


$$\begin{array}{l}CH.COOH\\ \|\\ CH.COOH\end{array}$$

Their isomerism is explained on p. 428.

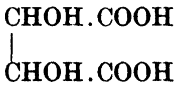
## THE HYDROXYDIBASIC AND POLYBASIC ACIDS

The most important hydroxydibasic acids are derivatives of succinic acid. The monohydroxy derivative is malic acid. The dihydroxy derivative is tartaric acid.



$$\begin{array}{l}CHOH.COOH\\ |\\ CH_2.COOH\end{array}$$

Malic acid



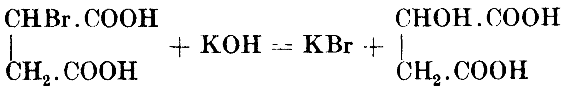
$$\begin{array}{l}CHOH.COOH\\ |\\ CHOH.COOH\end{array}$$

Tartaric acid

### Malic Acid

This is found in many fruits (sour grapes, apples, and mountain ash berries). The molecule of malic acid contains a carbon atom united to four different radicals, and it therefore exists in optically active forms (p. 421). The naturally occurring form is laevo-rotatory, the dextro-rotatory form being obtained by separation of the inactive racemic mixture.

The constitution of malic acid may be established by its formation by hydrolysis of monobromosuccinic acid.

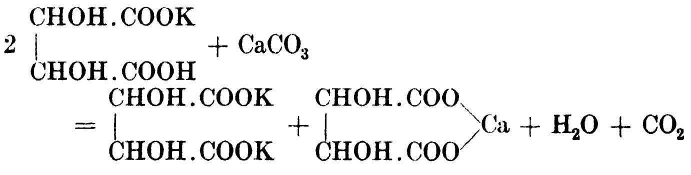


$$\begin{array}{l}\mathrm{CHBr.COOH}\\ |\\ \mathrm{CH_2.COOH}\end{array} + \mathrm{KOH} = \mathrm{KBr} + \begin{array}{l}\mathrm{CHOH.COOH}\\ |\\ \mathrm{CH_2.COOH}\end{array}$$

### Tartaric Acid

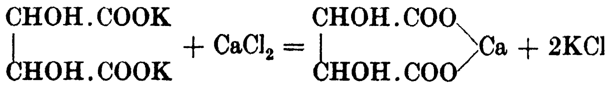
Tartaric acid contains two carbon atoms attached to four different radicals and, as shown on p. 424, two optically active forms (dextro- and laevo-rotatory) and two optically inactive forms of tartaric acid are obtainable, all represented by the formula on p. 413. The ordinary naturally occurring form of tartaric acid is dextro-rotatory. This is found in many fruits. During the fermentation of grape-juice, the sparingly soluble potassium acid tartrate separates out and is deposited at the bottom of the vats. The crude salt is known as *argol*, and pure potassium acid tartrate is obtained from it by recrystallization. Tartaric acid is obtained from argol in the following manner—

Argol is neutralized by heating with chalk and water, to form a mixture of soluble neutral potassium tartrate and insoluble calcium tartrate.



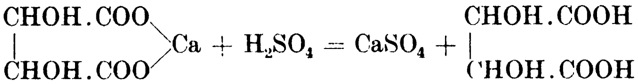
$$2\begin{array}{l}\mathrm{CHOH.COOK}\\ |\\ \mathrm{CHOH.COOH}\end{array} + \mathrm{CaCO_3} = \begin{array}{l}\mathrm{CHOH.COOK}\\ |\\ \mathrm{CHOH.COOK}\end{array} + \left.\begin{array}{l}\mathrm{CHOH.COO}\\ |\\ \mathrm{CHOH.COO}\end{array}\right\rangle \mathrm{Ca} + \mathrm{H_2O} + \mathrm{CO_2}$$

The calcium tartrate is removed by filtration and the dissolved potassium tartrate is then converted into calcium tartrate by addition of calcium chloride. The precipitated calcium tartrate is again collected by filtration.



$$\begin{array}{l}\mathrm{CHOH.COOK}\\ |\\ \mathrm{CHOH.COOK}\end{array} + \mathrm{CaCl_2} = \left.\begin{array}{l}\mathrm{CHOH.COO}\\ |\\ \mathrm{CHOH.COO}\end{array}\right\rangle \mathrm{Ca} + 2\mathrm{KCl}$$

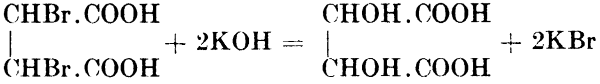
The calcium tartrate is decomposed with sulphuric acid, and after filtering from the calcium sulphate the solution of crude tartaric acid is concentrated by evaporation under reduced pressure until crystallization occurs. The acid is purified by recrystallization.



$$\begin{matrix}\text{CHOH.COO}\\ |\\ \text{CHOH.COO}\end{matrix}\!\!>\!\text{Ca} + H_2SO_4 = CaSO_4 + \begin{matrix}\text{CHOH.COOH}\\ |\\ \text{CHOH.COOH}\end{matrix}$$

Dextro-rotatory tartaric acid thus obtained may be converted into either of the two inactive forms by the action of heat on its aqueous solution; the laevo-rotatory form is obtainable by removing the dextro-rotatory fraction from the racemic mixture.

The constitution of tartaric acid is established by its synthesis from dibromosuccinic acid.



$$\begin{matrix}\text{CHBr.COOH}\\ |\\ \text{CHBr.COOH}\end{matrix} + 2KOH = \begin{matrix}\text{CHOH.COOH}\\ |\\ \text{CHOH.COOH}\end{matrix} + 2KBr$$

Dibromosuccinic acid Tartaric acid

PROPERTIES OF TARTARIC ACID

Ordinary (dextro-rotatory) tartaric acid crystallizes in prisms which are soluble in water and alcohol. (Tartaric acid can be detected as an impurity in Potassium Acid Tartrate B.P. by extraction with alcohol.) On heating it chars readily, and it darkens fairly rapidly when heated with concentrated sulphuric acid.

Tartaric acid is a reducing agent. It reduces ammoniacal silver nitrate solution forming a silver mirror.

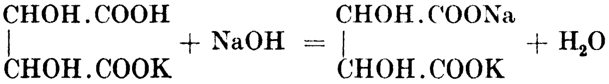
Tartaric acid forms complex compounds with many metals, which do not then give their ordinary reactions. [For example, copper is not precipitated from an alkaline solution containing tartrates. The resulting solution (Fehling's solution) on reduction gives a precipitate of cuprous oxide.]

A crystalline precipitate of calcium tartrate is obtained when calcium chloride is added to a neutral solution of a tartrate. Under similar conditions, citrates give a precipitate of calcium citrate only if the solution is boiled. (Calcium citrate is appreciably soluble in cold water, although less soluble in hot water.)

Tartaric Acid and the following salts are official substances—Potassium Hydrogen Tartrate ($KHC_4H_4O_6$); Sodium Potassium Tartrate ($KNaC_4H_4O_6$, $4H_2O$ prepared by neutralizing potassium acid tartrate with sodium carbonate); Potassium and Sodium Antimonyl Tartrates ($2K(SbO)C_4H_4O_6$, $H_2O$ and $Na(SbO)C_4H_4O_6$) prepared by reacting on potassium or sodium hydrogen tartrates with antimony oxide); and Sodium Bismuthyl Tartrate prepared similarly from bismuth hydroxide The last named official substance has a variable composition (limits of bismuth 35·0 to 42·0 per cent).

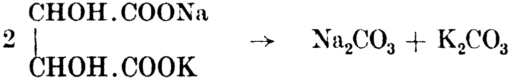
Tartaric Acid and Potassium Acid Tartrate are assayed on their acidity.

$$\mathrm{(CHOH.COOH)_2 + 2NaOH = (CHOH.COONa)_2 + 2H_2O}$$



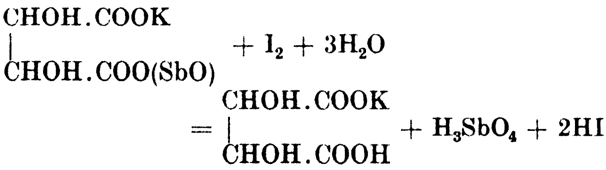
$$\begin{array}{l}\mathrm{CHOH.COOH}\\ \vert \\ \mathrm{CHOH.COOK}\end{array} + \mathrm{NaOH} = \begin{array}{l}\mathrm{CHOH.COONa}\\ \vert \\ \mathrm{CHOH.COOK}\end{array} + \mathrm{H_2O}$$

Sodium Potassium Tartrate is ignited and the carbonates formed are determined by dissolving in excess standard acid and back titrating the excess with standard alkali.



$$2\begin{array}{l}\mathrm{CHOH.COONa}\\ \vert \\ \mathrm{CHOH.COOK}\end{array} \rightarrow \mathrm{Na_2CO_3 + K_2CO_3}$$

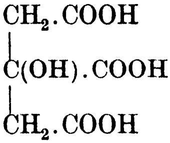
The antimony compounds are assayed on their antimony content by iodine titration while the bismuth compound is determined gravimetrically (p. 217).



$$\begin{array}{l}\mathrm{CHOH.COOK}\\ \vert \\ \mathrm{CHOH.COO(SbO)}\end{array} + \mathrm{I_2 + 3H_2O} = \begin{array}{l}\mathrm{CHOH.COOK}\\ \vert \\ \mathrm{CHOH.COOH}\end{array} + \mathrm{H_3SbO_4 + 2HI}$$

The amount of iron and copper present as impurity in Tartaric Acid and Potassium Acid Tartrate is controlled by adding ammonia and sodium sulphide to two solutions, one of which also contains potassium cyanide. In the one solution lead, iron, and copper are precipitated, but in the presence of potassium cyanide only lead is precipitated so that any difference in colour between the two solutions is due to the iron and copper present.

### Citric Acid



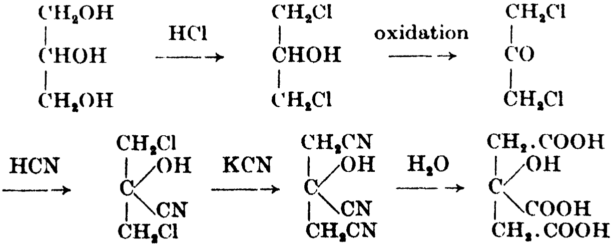
$$\begin{array}{l} CH_2.COOH \\ | \\ C(OH).COOH \\ | \\ CH_2.COOH \end{array}$$

This is a tribasic monohydroxy acid of the above constitution. It is present in the juices of citrus fruits, and is prepared from lemon juice by neutralization with milk of lime. The precipitated calcium citrate is collected and decomposed with sulphuric acid. It is also obtained by the fermentation of sugars by *aspergillus niger.*

$$C_{12}H_{22}O_{11} + 6O = 2C_6H_8O_7 + 3H_2O$$

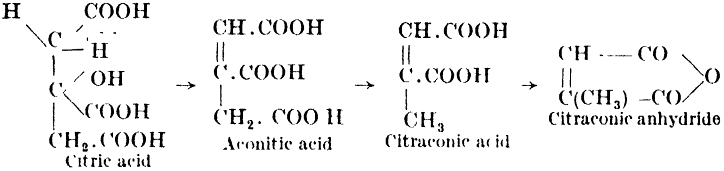
Owing to a side reaction some oxalic acid may be formed during this fermentation. (The official test for the presence of oxalates in citrates is carried out by precipitation of calcium oxalate with calcium chloride.)

The constitution of citric acid follows from its synthesis by means of the following series of reactions. By the addition of hydrogen cyanide to symmetrical dichloro-acetone (which is obtained from glycerol), followed by reaction with potassium cyanide, a substance is obtained which on hydrolysis yields citric acid.



Citric acid does not char so readily on heating as tartaric acid, and the presence of tartaric acid as an adulterant may be detected by observation of the rate of charring with concentrated sulphuric acid.

If citric acid is heated carefully, it breaks down into simpler substances according to the scheme—



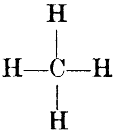
Citric Acid, Sodium and Potassium Citrates, and the complex compound Iron and Ammonium Citrate, are official in the *British Pharmacopœia.* Citric Acid is assayed by direct titration with standard alkali (using thymol blue as indicator), while the alkali citrates are assayed by ignition to carbonate. After carbonization, the residue is dissolved in excess standard sulphuric acid, the excess being determined by back titration. The complex salt is assayed on its ferric iron content.

# CHAPTER XXVI

# STEREOCHEMISTRY

CERTAIN substances possess the power of rotation of the plane of polarized light, and on pp. 107–110 methods have been described for the measurement of optical rotation. This section deals with those structural arrangements which cause the rotation.

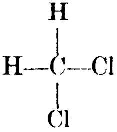
The four radicals which are attached to a carbon atom have been represented as lying in a plane (the plane of the paper); e.g. the formula of methane has been written thus—



$$\begin{array}{ccc} & H & \\ & | & \\ H- & C & -H \\ & | & \\ & H & \end{array}$$

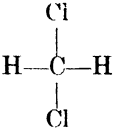
This method of writing the formula has been adopted for convenience, but it does not represent the true arrangement in which the four radicals are grouped around the carbon atom.

If the co-planar arrangement existed it would be possible to obtain two isomeric dichloromethanes thus—



$$\begin{array}{ccc} & H & \\ & | & \\ H- & C & -Cl \\ & | & \\ & Cl & \end{array}$$

Cis form

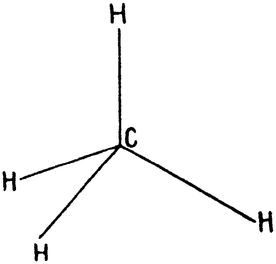


$$\begin{array}{ccc} & Cl & \\ & | & \\ H- & C & -H \\ & | & \\ & Cl & \end{array}$$

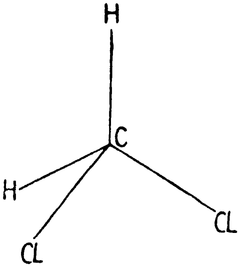
Trans form

These isomeric forms cannot be obtained.

In reality, the four radicals are arranged spatially (in three dimensions) about the carbon atom, so that the resulting molecule is solid rather than flat; e.g. the formula for methane should be represented as in the diagram.

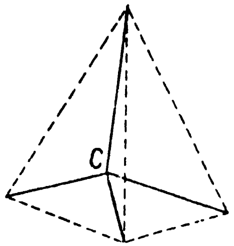


The formula of dichloromethane is represented thus—

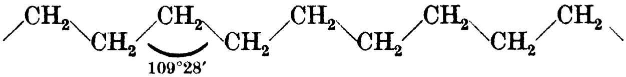


With this arrangement, only one substance can exist.

The observed equivalence of the four hydrogen atoms in the methane molecule indicates that they are symmetrically disposed with reference to the carbon atom. This symmetrical arrangement is obtained when the carbon atom is placed at the centre of a regular tetrahedron, and a hydrogen atom at each of the four corners. It was first suggested in 1874 by *Van't Hoff* that the four valencies of carbon were directed towards the corners of a regular tetrahedron. Almost simultaneously *Le Bel* suggested that the carbon valencies were arranged spatially, and Van't Hoff and Le Bel were able to explain the optical activity of carbon compounds on these assumptions.



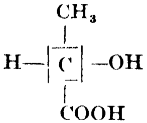
The hypothesis was substantiated when the diamond was shown by X-ray analysis to be built up of carbon atoms each of which is linked to four other carbon atoms arranged in a regular tetrahedron (p. 219). In accordance with this hypothesis, the valency angles of carbon are at 109° 28′ (the tetrahedral angle). It follows that in a chain the carbon atoms do not lie in the same straight line but form a zigzag arrangement as in the diagram.



Elements other than carbon may show similar spatial arrangements, and give rise to similar effects.

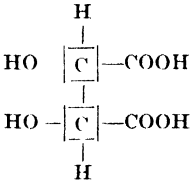
*Carbon compounds exhibit optical activity when their molecules contain at least one carbon atom united to four atoms or radicals, all of which are different.*

*Examples.* Lactic acid contains one carbon atom united to four different radicals. Tartaric acid contains two carbon atoms united to four different radicals. Glucose contains four carbon atoms united to four different radicals.



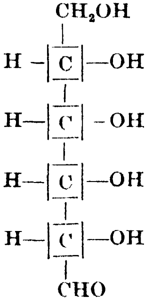
$$\begin{array}{c} CH_3 \\ | \\ H—\boxed{C}—OH \\ | \\ COOH \end{array}$$

Lactic acid



$$\begin{array}{c} H \\ | \\ HO\ \boxed{C}—COOH \\ | \\ HO—\boxed{C}—COOH \\ | \\ H \end{array}$$

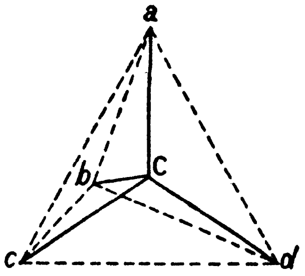
Tartaric acid



$$\begin{array}{c} CH_2OH \\ | \\ H—\boxed{C}—OH \\ | \\ H—\boxed{C}—OH \\ | \\ H—\boxed{C}—OH \\ | \\ H—\boxed{C}—OH \\ | \\ CHO \end{array}$$

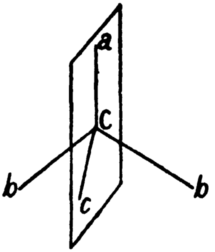
Glucose

The spatial formula of such a carbon atom can be represented by an arrangement as in the diagram where the different radicals are indicated by the letters *a*, *b*, *c*, and *d*. It is not possible to divide this molecular arrangement by any plane

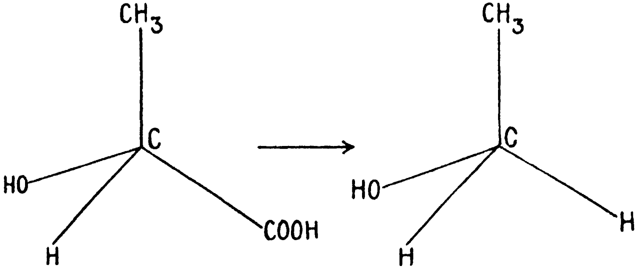


in such a way that the portions of the molecule on either side of the plane correspond exactly. The molecule is without symmetry. A carbon atom which is attached to four different radicals, and which forms an arrangement possessing no plane of symmetry is called an *asymmetric carbon atom.* (Asymmetry=absence of symmetry.)

Atoms which are not united to four radicals all different are not asymmetric. The resultant molecule can be divided into two equivalent portions. For example, with two similar radicals the molecule can be divided into two corresponding halves as in the diagram.



*Optical activity is exhibited by those compounds which possess asymmetric molecules. When asymmetry is caused to disappear (e.g. by altering the groups attached to an asymmetric carbon atom so that all four are no longer different) optical activity disappears at the same time.*



Lactic acid:
asymmetrical and optically active

Ethyl alcohol:
symmetrical and not optically active

The optical activity of substances such as quartz confirms the correlation between absence of symmetry and optical activity. Although the molecules of such substances are quite symmetrical, the crystals contain an asymmetrical arrangement of the molecules so that the crystal becomes optically active. On melting or in solution the optical activity of these substances disappears. When the molecule is asymmetric (as in the carbon compounds mentioned above) optical activity persists whether the substance is in the solid, liquid, or vapour state or in solution.

The mirror image of an object which possesses a plane of symmetry can be made to correspond with the object itself. The mirror image of an asymmetric object cannot be superposed on the object to occupy exactly the same position and arrangement in space. The object and the mirror image are related in a similar manner to that in which a right hand is related to a left hand.

Consequently, with a compound whose molecule is asymmetric, it is possible to obtain two non-superposable molecular arrangements (corresponding to two different compounds) related as object and mirror image. Owing to the close similarity of these two molecular arrangements the corresponding compounds would be expected to have almost identical properties.

A compound containing one asymmetric carbon atom (e.g. lactic acid) is found to exist in three isomeric forms, two optically active, and one optically inactive. The two optically active forms have similar physical and chemical properties and differ only in their behaviour to polarized light. One form rotates the plane of polarization to the right, the other rotates the plane of polarization to the left. Under equivalent conditions, the dextro- and laevo-rotations of the two forms are exactly equal but of opposite sign. These two forms correspond to the object and mirror image molecular arrangements. [They are called *enantiomorphous* forms (cf. *enantios*, opposite; *morphos*, form).]

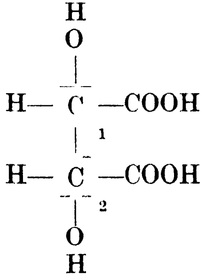
The third isomeric form is found to be a mixture in equal proportions of the two optically active forms. Its optical inactivity is due to the exact neutralization of the dextro- and laevo-rotations. It is said to be inactive by *external compensation*. (It is sometimes called the *racemic* or *dl* form or racemic mixture.) The physical and chemical properties of this mixture differ slightly from those of its optically active constituents. (For the separation of the two optically active constituents from a racemic mixture, see p. 426.)

As this type of *optical isomerism* arises owing to the spatial arrangement of the atoms within the molecule, it is often called *stereoisomerism* (the isomers being known as stereoisomers).

### Stereoisomerism of Tartaric Acid

Tartaric acid exists in four modifications, two of which are optically active and two inactive. Ordinary tartaric acid is the dextro-rotatory isomer. The corresponding laevo form can be obtained by separating the optically active components from the inactive racemic mixture. The other inactive form (mesotartaric acid) is not capable of being split into two optically active forms.

Tartaric acid contains two asymmetric carbon atoms



$$\begin{array}{ccc} & H & \\ & O & \\ & | & \\ H- & C & -COOH \\ & |\;{}^{1} & \\ H- & C & -COOH \\ & |\;{}^{2} & \\ & O & \\ & H & \end{array}$$

If the asymmetric groupings around the two carbon atoms are considered independently of one another the following combinations are possible.

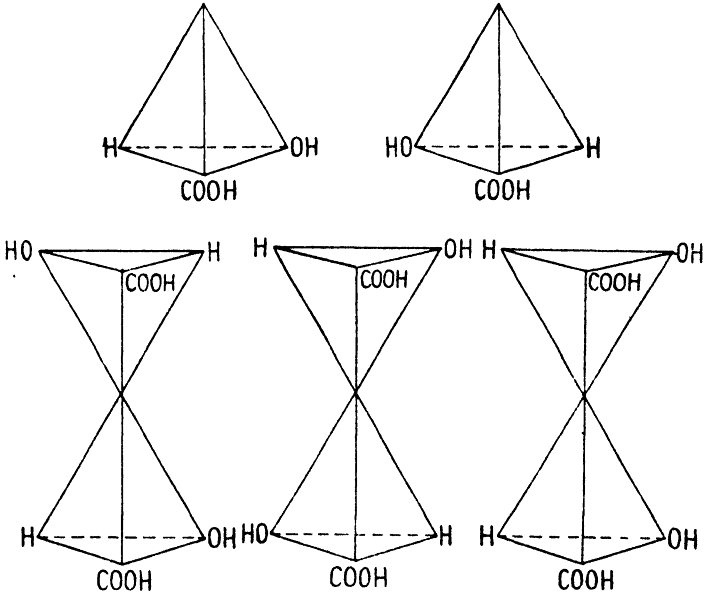
(*a*) Dextro (1) + Dextro (2).
(*b*) Dextro (1) + Laevo (2).
(*c*) Laevo (1) + Dextro (2).
(*d*) Laevo (1) + Laevo (2).

The groupings attached to the two asymmetric atoms 1 and 2 are identical, so that the compound represented by arrangements (*b*) and (*c*) is optically inactive.

This inactive form differs from the inactive racemic form (obtained by mixing the dextro and laevo forms (*a*) and (*d*) in equal proportions), for it is inactive through mutual neutralization of two active groupings inside the same molecule.

It is said to be *inactive by internal compensation*, in contrast to the racemic form which is *inactive by external compensation.* The internally compensated form, unlike the externally compensated form, cannot be separated into two optically active forms.

The molecules of dextro-rotatory, laevo-rotatory and internally compensated inactive tartaric acid are represented in the diagram. In the latter form, the opposing configurations form an arrangement containing a plane of symmetry, illustrating the optical inactivity of the compound.



*d* + *d* = D tartaric acid  *l* + *l* = L tartaric acid  *l* + *d* = mesotartaric acid

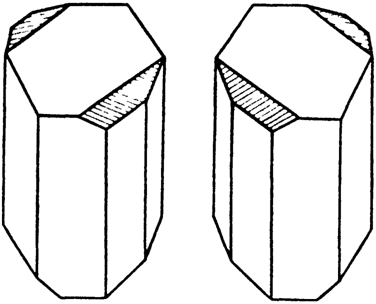
In compounds containing more than two asymmetric carbon atoms, it is possible to predict the number of isomeric forms obtainable by considering the effects of each asymmetric grouping independently, as in the case of tartaric acid. For example there are sixteen stereoisomeric aldose sugars. Mainly through the work of *Emil Fischer* all these stereoisomers have been isolated, and their configurations determined, e.g. dextro glucose may be represented by the formula

$$\mathrm{CH_2OH.\overset{\mathit{d}}{C}HOH.\overset{\mathit{d}}{C}HOH.\overset{\mathit{l}}{C}HOH.\overset{\mathit{d}}{C}HOH.CHO}$$

where the letters *d* and *l* represent the rotatory effect of the groupings around the particular carbon atom.

## Resolution of Racemic Compounds

Substances which are capable of exhibiting optical activity usually occur naturally in an optically active form. When these substances are synthesized in the laboratory from inactive sources the racemic mixture is obtained. In order to obtain a product which is identical with the natural form the synthetic mixture must be *resolved*, i.e. separated into its active components. Owing to the similarity in the physical and chemical properties of the dextro- and laevo-rotatory forms no direct separation is possible. The resolution can be carried out by three indirect methods.



(*a*) (*b*)

FIG. 28. CRYSTALS OF (*a*) SODIUM AMMONIUM *d* TARTRATE, (*b*) SODIUM AMMONIUM *l* TARTRATE

(1) The first separation of the racemic form into its active constituents was carried out by *Pasteur* in 1848. He found that when the sodium ammonium salt of racemic tartaric acid was allowed to crystallize at a fairly low temperature, the crystals which separated could be sorted out under the microscope into two groups, one of which was composed of crystals which were the mirror images of those in the other group. (Fig. 28.)

Pasteur found that one group of crystals consisted of the salt of ordinary dextro-rotatory tartaric acid, while the other group of crystals consisted of the corresponding laevo-tartaric acid salt.

This method of resolution by sorting out mirror image crystals is not of very general application.

(2) Pasteur found a second method of separation. A mould or fungus may be found which grows on one optically active form only, so that in a racemic mixture one form is destroyed and the other remains, e.g. *pencillium glaucum* when grown in a solution of racemic tartaric acid destroys the dextro form and leaves the laevo form unchanged.

This method of resolution suffers from the disadvantage that one optically active isomer is lost in order to obtain the other.

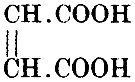
(3) The most important method for the resolution of racemic forms is the crystallization of a suitable salt of the substance with another optically active substance. If the substance to be resolved is an acid it is converted into its salt with an optically active base (e.g. *l* brucine); if the substance to be resolved is a base it is converted into its salt with an optically active acid (e.g. *d* tartaric acid).

For example, suppose the resolution of an inactive acid is being carried out by means of *l* brucine. The inactive acid (*d* acid + *l* acid) is converted into its *l* brucine salt, so that there is present *d* acid; *l* brucine salt, and *l* acid; *l* brucine salt. These two compounds are not optical antipodes (for the corresponding compound to *d* acid; *l* brucine would be *l* acid; *d* brucine), and therefore their physical and chemical properties are no longer identical. One form is more soluble than the other, and the two forms can be separated by fractional crystallization. The two optically active forms of the acid can then be liberated from their alkaloidal salts.

The physiological activity of the two forms of an optically active substance are often widely different. [Compare for example atropine (the *dl* form) with hyoscyamine (the *l* form).] This effect may be attributed to other optically active substances present in the living organism, which behave differently towards the dextro- and laevo-rotatory forms of the compound.

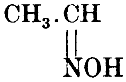
## GEOMETRICAL ISOMERISM

The conception of the spatial arrangement of the four valencies of carbon also explains the existence of geometrical isomerism, which occurs in compounds containing a double bond between two carbon atoms or between a carbon and a nitrogen atom, e.g.



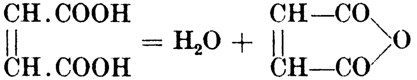
$$\begin{array}{l} CH.COOH \\ \| \\ CH.COOH \end{array}$$

(1)



$$\begin{array}{l} CH_3.CH \\ \quad\;\; \| \\ \quad\;\; NOH \end{array}$$

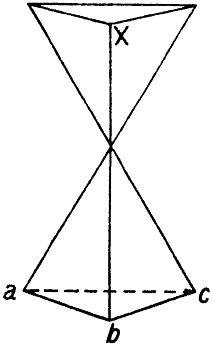
It occurs when the two radicals attached to each double-bonded carbon atom are different. The two compounds (maleic and fumaric acid) represented by the formula (1) form an example of this type of isomerism. Maleic and fumaric acids differ in their physical and chemical properties, e.g. only maleic acid forms an anhydride,



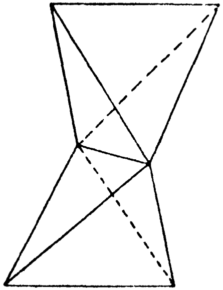
$$\begin{array}{l} CH.COOH \\ \| \\ CH.COOH \end{array} = H_2O + \begin{array}{l} CH{-}CO \\ \| \qquad\quad\;\; \rangle O \\ CH{-}CO \end{array}$$

Maleic acid Maleic anhydride

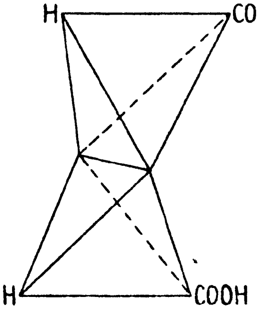
In accordance with the tetrahedral model of the carbon atom, the single bond (C—C) is represented by two tetrahedra joined at the corners, e.g. ethane is represented as in the diagram.



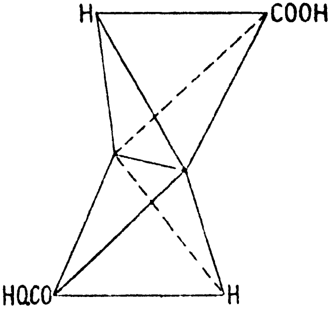
In order to explain the non-existence of a large number of isomeric ethane derivatives depending on the relative position of the two tetrahedra (e.g. atom *X* opposite either *a*, *b* or *c*) it is necessary to assume that the two tetrahedra are quite free to rotate about their common axis. The existence of geometrical isomers is due to the restriction of the free rotation on the formation of a double bond. Two carbon atoms united by a double bond are represented by two tetrahedra joined edge to edge. Under these conditions, the only motion of the tetrahedra is an oscillation about the line of contact.



It is possible to have two arrangements, which cannot be inter-converted without disruption of the double bond.



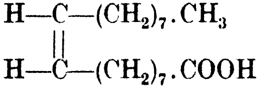
(1) Maleic acid



(2) Fumaric acid

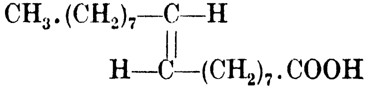
In arrangement (1) the two like groups are near to one another (the *cis* position); in arrangement (2) the two like groups are separated from one another (the *trans* position). As maleic acid forms an anhydride the two carboxyl groups must be close together in this acid, which is therefore the cis-isomer. Fumaric acid (which does not form an anhydride) is the trans-isomer.

The geometrical isomer corresponding to oleic acid is called elaidic acid. In this case oleic acid is the cis-isomer while elaidic acid is the trans form.



$$\begin{array}{l}H\text{—}C\text{—}(CH_2)_7.CH_3\\ \quad\ \ \|\\ H\text{—}C\text{—}(CH_2)_7.COOH\end{array}$$

Oleic acid



$$\begin{array}{r}CH_3.(CH_2)_7\text{—}C\text{—}H\qquad\qquad\qquad\\ \|\qquad\qquad\qquad\qquad\\ H\text{—}C\text{—}(CH_2)_7.COOH\end{array}$$

Elaidic acid

## CHAPTER XXVII

# THE ALIPHATIC NITROGEN COMPOUNDS

## THE ALIPHATIC AMINES

THE aliphatic amines are derivatives of ammonia obtained by the replacement of the hydrogen atoms by alkyl radicals. One, two, or three hydrogen atoms may be substituted forming compounds of the type $R—NH_2$ (primary amines), $\genfrac{}{}{0pt}{}{R\diagdown}{R\diagup}NH$ (secondary amines), and $\begin{smallmatrix}R\diagdown\\ R—N\\ R\diagup\end{smallmatrix}$ (tertiary amines). It is also possible to obtain quaternary ammonium salts in which the four hydrogen atoms of ammonium chloride have been replaced by alkyl radicals, such as $\genfrac{}{}{0pt}{}{R\diagdown}{R\diagup}N\genfrac{}{}{0pt}{}{\diagup R}{\diagdown R}\ Cl$. (The alkyl radicals need not necessarily be the same in these compounds.)

### Preparation of Amines

(1) Amines may be prepared by the direct substitution of ammonia by reaction with alkyl halides in alcoholic solution. Primary, secondary, tertiary, or quaternary compounds can be obtained by successive substitution.

$$NH_2H + CH_3Br = \underset{\text{Methylamine}}{NH_2CH_3} + HBr$$

$$NH_2CH_3 + CH_3Br = \underset{\text{Dimethylamine}}{(CH_3)_2NH} + HBr$$

$$(CH_3)_2NH + CH_3Br = \underset{\text{Trimethylamine}}{(CH_3)_3N} + HBr$$

$$(CH_3)_3N + CH_3Br = \underset{\text{Tetramethylammonium bromide}}{(CH_3)_4NBr}$$

In many cases all four products are formed in varying proportions, and their separation is often difficult. The primary, secondary, and tertiary bases are liberated from their salts by adding sodium hydroxide and they can then be distilled away from the unchanged quaternary salt. In order to separate the primary, secondary, and tertiary amines chemical methods must be used, e.g. by reacting on the mixture with nitrous acid, the primary amine is destroyed, the secondary amine is converted into a nitrosamine, and the tertiary amine remains unchanged. On extracting with an organic solvent in acid solution, the nitrosamine from the secondary amine passes into the organic solvent layer, while the tertiary amine remains in the aqueous layer as a salt. After separation, the secondary amine can be recovered from the nitrosamine by reduction.

(2) Primary amines are more conveniently prepared from acid amides by reaction with bromine in presence of potassium hydroxide (*Hofmann* reaction).

The first reaction produces the bromine derivative of the acid amide.

$$\underset{\text{Acetamide}}{CH_3.CONH_2} + Br_2 = \underset{\text{Monobromacetamide}}{CH_3.CONHBr} + HBr$$

This substance then loses a molecule of hydrogen bromide, and at the same time undergoes a molecular rearrangement.

$$CH_3.CONHBr = \underset{\substack{\text{Methyl}\\\text{isocyanate}}}{CH_3NCO} + HBr$$

The isocyanate thus formed yields on hydrolysis the primary amine.

$$CH_3NCO + 2KOH = CH_3NH_2 + K_2CO_3$$

The amine formed contains one carbon atom less than the original acid amide.

$$CH_3.CONH_2 \rightarrow CH_3NH_2$$

(3) Primary amines are also obtained when certain other compounds containing a nitrogen atom linked directly to a carbon atom are reduced, e.g. nitro-paraffins (p. 435), cyanides (p. 436), and oximes (p. 373).

$$CH_3NO_2 + 3H_2 = CH_3NH_2 + 2H_2O$$

$$CH_3CN + 2H_2 = CH_3.CH_2NH_2$$

$$CH_3.CH{=}NOH + 2H_2 = CH_3.CH_2NH_2 + H_2O$$

## Properties of Amines

The amines resemble ammonia in many ways; the lower members are gases, very soluble in water to give alkaline solutions. They possess characteristic odours. The amines are strongly basic substances and like ammonia form salts by the addition of the acid molecule.

$$CH_3NH_2 + HCl = \underset{\text{Methylamine hydrochloride}}{CH_3NH_3Cl}$$

$$NH_3 + HCl = NH_4Cl$$

The amines are stronger bases than ammonia and the strength of the base increases with increased substitution, i.e. in order of strength ammonia $<$ primary amine $<$ secondary amine $<$ tertiary amine $<$ quaternary amine. The quaternary bases are so strong that they are not displaced from their salts by caustic soda or potash.

The most important distinction between primary, secondary, and tertiary amines lies in their behaviour towards nitrous acid.

(*a*) The primary amines react to give an immediate evolution of nitrogen, and the alcohol is formed.

$$CH_3NH_2 + HNO_2 = CH_3OH + H_2O + N_2$$

$$\begin{array}{l} CH_3\text{—}N\text{—}H_2 \\ HO\text{—}N\text{—}O \end{array} = CH_3OH + N_2 + H_2O$$

(*b*) The secondary amines react to form a nitrosamine (which contains the grouping N—N=O).

$$(CH_3)_2NH + HNO_2 = (CH_3)_2N.NO + H_2O$$

$$(CH_3)_2N\,\underline{H + HO}\text{—}N=O = (CH_3)_2N\text{—}N=O + H_2O$$

The nitrosamines are neutral substances which are insoluble in water but soluble in organic solvents. On reduction they form the original secondary amine.

$$2(CH_3)_2N.N=O + 3H_2 = 2(CH_3)_2NH + N_2 + 2H_2O$$

(c) The tertiary amines do not react with nitrous acid.

The primary amines may also be distinguished from the other amines by their reaction with chloroform and potassium hydroxide, whereby poisonous and strongly smelling isocyanides are obtained.

$$CH_3NH_2 + 3KOH + CHCl_3 = \underset{\substack{\text{Methyl}\\ \text{isocyanide}}}{CH_3NC} + 3KCl + 3H_2O$$

The primary and secondary amines react with acid chlorides to form derivatives in which a hydrogen atom of the amine is replaced by an acyl radical (cf. p. 499).

*Ethanolamine* is a hydroxy-amine of the constitution $CH_2OH.CH_2NH_2$ and can be prepared by the action of aqueous ammonia on ethylene oxide.

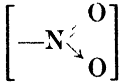
$$(CH_2)_2O + NH_3 = CH_2OH.CH_2NH_2$$

Being an amine, it has basic properties and forms salts (e.g. ethanolamine oleate). It can be assayed by a back titration acid-alkali method.

*Ethylene diamine* ($CH_2NH_2.CH_2NH_2$) can be prepared by the action of ammonia on ethylene dichloride

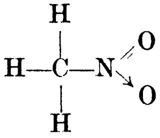
$$CH_2Cl.CH_2Cl + 2NH_3 = CH_2NH_2.CH_2NH_2 + 2HCl$$

## THE NITROPARAFFINS

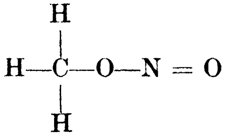
Nitroparaffins contain the nitro group  $\left[-\mathrm{N}\begin{matrix}\diagup\mathrm{O}\\ \searrow\mathrm{O}\end{matrix}\right]$ attached to an alkyl radical, e.g. nitromethane ($CH_3NO_2$). They are prepared in the laboratory by the reaction of *silver* nitrite on an alkyl halide, and not by the action of nitric acid on a paraffin hydrocarbon (cf. p. 495). Some of the simpler aliphatic nitro compounds are, however, prepared on an industrial scale by nitration *in the vapour phase.*

$$AgNO_2 + C_2H_5I = AgI + \underset{\text{Nitro-ethane}}{C_2H_5NO_2}$$

The isomeric alkyl nitrites (p. 396) are formed by the reaction of an alkyl halide with *sodium* nitrite. The nitroparaffins differ from the alkyl nitrites in that the nitrogen atom is linked directly to a carbon atom, and not through an oxygen atom as in the nitrites.



Nitromethane, quinquevalent nitrogen



Methyl nitrite, tervalent nitrogen

The nitroparaffins are not affected by alkalis, and in this respect they differ from the nitrites which are readily hydrolyzed.

$$C_2H_5ONO + NaOH = NaNO_2 + C_2H_5OH$$

On reduction the nitroparaffins are converted to the primary amines (cf. p. 432).

$$C_2H_5NO_2 + 3H_2 = C_2H_5NH_2 + 2H_2O$$

## THE ALKYL CYANIDES

The alkyl cyanides are also called *nitriles*. (In this case they are named according to the acid they yield on hydrolysis; thus methyl cyanide = acetonitrile.) They may be prepared by the following methods—

(1) By the dehydration of amides, usually by heating with phosphorus pentoxide.

$$CH_3.CONH_2 = CH_3CN + H_2O$$

(2) By the action of potassium cyanide on an alkyl halide.

$$CH_3I + KCN = CH_3CN + KI$$

### Properties of the Nitriles

The most important reaction of the nitriles is their conversion into acids by hydrolysis. When warmed either with acids or alkalis two molecules of water are taken up and the ammonium salt of the acid is formed, the free acid being obtained from this salt.

$$\underset{\substack{\text{Methyl cyanide}\\\text{or acetonitrile}}}{CH_3CN} + 2H_2O = CH_3.COONH_4$$

$$2CH_3.COONH_4 + H_2SO_4 = \underset{\text{Acetic acid}}{2CH_3.COOH} + (NH_4)_2SO_4$$

This reaction affords an important method of synthesis of acids.

By more gentle hydrolysis (e.g. using hydrogen peroxide) only one molecule of water is taken up by the nitrile and the acid amide is obtained.

$$CH_3CN + H_2O = CH_3.CONH_2$$

On reduction the nitriles yield primary amines.

$$CH_3CN + 2H_2 = CH_3.CH_2NH_2$$

**The Alkyl Isocyanides**

The isocyanides or isonitriles (or carbylamines) differ from the nitriles in having the nitrogen atom attached to the alkyl group. They contain a bivalent carbon atom (cf. p. 223).

$$\underset{\text{Nitrile or cyanide}}{CH_3{-}C{\equiv}N} \qquad \underset{\text{Isonitrile, isocyanide or carbylamine}}{CH_3{-}N{=}C}$$

They may be prepared from the alkyl halide by using *silver* cyanide instead of *potassium* cyanide.

$$AgNC + CH_3I = CH_3NC + AgI$$

They are also prepared by the carbylamine reaction from chloroform and primary amines.

$$CH_3NH_2 + 3KOH + CHCl_3 = \underset{\substack{\text{Methyl}\\ \text{isocyanide}}}{CH_3NC} + 3KCl + 3H_2O$$

The properties of the isonitriles differ from those of the nitriles. They are more toxic and have characteristic unpleasant smells. They are hydrolyzed by acids to form amines and on reduction they yield secondary amines.

$$CH_3NC + 2H_2O = CH_3NH_2 + HCOOH$$

$$CH_3NC + 2H_2 = (CH_3)_2NH$$

## THE ACID AMIDES

Acid amides can be regarded as derivatives of ammonia in which the hydrogen atom has been replaced by acyl groups, or as acids in which the hydroxyl group has been replaced by an amino group.

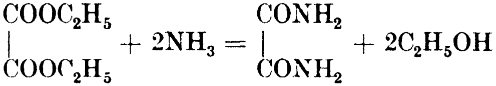
Thus acetamide can be regarded as the acetyl derivative of ammonia $CH_3.CO{-}NH_2$, or the amino derivative of acetic acid $CH_3.COOH \rightarrow CH_3.CONH_2$.

## Preparation of Acid Amides

(1) Acid amides are prepared from ammonia by the action of acid chlorides or anhydrides.

$$CH_3.COCl + NH_3 = CH_3.CONH_2 + HCl$$

In some cases the ester can be used instead of the acid chloride, e.g. the additon of ammonia to ethyl oxalate causes a precipitate of oxamide to be formed.



$$\begin{array}{l}COOC_2H_5\\ |\\ COOC_2H_5\end{array} + 2NH_3 = \begin{array}{l}CONH_2\\ |\\ CONH_2\end{array} + 2C_2H_5OH$$

(2) Many acid amides are conveniently prepared by dehydration of the ammonium salt of the corresponding acid (often by heating).

$$CH_3.COONH_4 = CH_3.CONH_2 + H_2O$$

(3) Acid amides are also obtained by the partial hydrolysis of nitriles.

## Physical Properties of Amides

The lowest member of the series (formamide $HCONH_2$) is liquid at ordinary temperatures, but the higher members are crystalline solids, many being soluble in water. Acetamide ($CH_3.CONH_2$) when pure forms odourless crystals, but ordinary specimens have a strong characteristic odour.

## Chemical Properties of the Amides

(1) Amides, unlike the amines, show few basic properties. They do not form stable salts with acids.

(2) Amides resemble the primary amines in their reaction with nitrous acid. Nitrogen is evolved, and the amino group is replaced by the hydroxyl group to form the acid.

$$CH_3.CONH_2 + HNO_2 = CH_3.COOH + N_2 + H_2O$$

(3) Amides are easily hydrolyzed to form the ammonium salts of acids, and dehydrated to form the cyanides. In these

reactions the amides are intermediate between these two compounds.

*Hydrolysis* →

Cyanides Amides Ammonium salts

← *Dehydration*

The evolution of ammonia when heated with alkalis is often uesd as a test for amides.

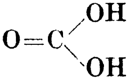
$$CH_3.CONH_2 + H_2O = CH_3.COONH_4$$

$$CH_3.COONH_4 + NaOH = CH_3.COONa + NH_3 + H_2O$$

(4) Amides react with bromine and potassium hydroxide to form the primary amine (p. 432).

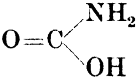
## Amides of Carbonic Acid

Carbonic acid is a dibasic acid, and thus it can form a mono-amide when one hydroxyl group is replaced by the amino group, and a di-amide when both hydroxyl groups are replaced.



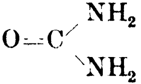
$$O{=}C\begin{matrix}\diagup OH\\ \diagdown OH\end{matrix}$$

Carbonic acid



$$O{=}C\begin{matrix}\diagup NH_2\\ \diagdown OH\end{matrix}$$

Carbamic acid



$$O{=}C\begin{matrix}\diagup NH_2\\ \diagdown NH_2\end{matrix}$$

Urea

The mono-amide possesses acid properties. It is called *carbamic acid.* It is not known in the free state, but its salts and esters are important, ammonium carbamate being one of the constituents of commercial ammonium carbonate, while ethyl carbamate and the other esters are the *urethanes.* (The name urethane is given to ethyl carbamate.) The di-amide of carbonic acid is *urea.*

### THE URETHANES

*Urethane* is prepared from ethyl carbonate or ethyl chloroformate and ammonia in accordance with the general methods for the preparation of acid amides.

$$C_2H_5O.COOC_2H_5 + NH_3 = C_2H_5OH + NH_2.COOC_2H_5$$

$$Cl.COOC_2H_5 + NH_3 = HCl + NH_2.COOC_2H_5$$

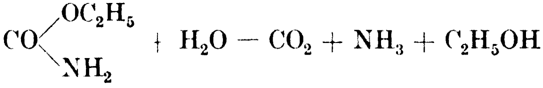
*Diphenan* is the corresponding *p*.benzylphenyl ester of carbamic acid and is prepared by a corresponding reaction.

$$\underset{p\text{.Benzylphenyl chloroformate}}{Cl.COOC_6H_4.CH_2.C_6H_5} + NH_3 = HCl + \underset{\text{Diphenan}}{NH_2.COOC_6H_4.CH_2.C_6H_5}$$

Some urethane derivatives can be prepared by the action of alcohols on urea.

$$NH_2.CONH_2 + ROH = NH_2.COOR + NH_3$$

The urethanes are crystalline solids. They can be regarded as both amides and esters, and on hydrolysis yield carbonic acid, ammonia and the corresponding alcohol.



$$CO\begin{cases} OC_2H_5 \\ NH_2 \end{cases} + H_2O = CO_2 + NH_3 + C_2H_5OH$$

*Carbachol* is both a urethane and a quaternary ammonium salt. It is prepared by acting with trimethylamine on the chloro-urethane which may be obtained by the action of urea on ethylene chlorohydrin.

$$NH_2.CO.NH_2 + HOCH_2.CH_2Cl = \underset{\beta\text{ Chloroethyl carbamate}}{NH_2.COOCH_2.CH_2Cl} + NH_3$$

$$NH_2.COOCH_2.CH_2Cl + N(CH_3)_3 = \underset{\text{Carbachol}}{NH_2.COOCH_2.CH_2N(CH_3)_3Cl}$$

*Neostigmine* is a more complex urethane-substituted ammonium salt type of compound.

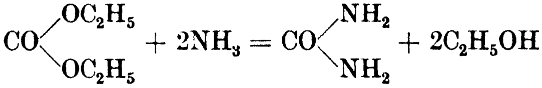
## Urea

Urea was the first substance of organic origin which was synthesized in the laboratory from inorganic sources (p. 317). It occurs in the urine of man and other mammals.

### PREPARATION OF UREA

Urea may be obtained from urine by evaporation and extraction as the nitric acid salt. The following synthetic methods can be used for the preparation of urea.

(1) In accordance with the general methods for the preparation of the acid amides, urea can be obtained by the action of ammonia on ethyl carbonate or carbonyl chloride.



$$CO\begin{matrix}\diagup OC_2H_5\\ \diagdown OC_2H_5\end{matrix} + 2NH_3 = CO\begin{matrix}\diagup NH_2\\ \diagdown NH_2\end{matrix} + 2C_2H_5OH$$

$$COCl_2 + 2NH_3 = CO(NH_2)_2 + 2HCl$$

Alkyl derivatives of urea can be obtained by similar reactions using amines instead of ammonia

$$COCl_2 + \underset{\text{Methylamine}}{2NH_2CH_3} = 2HCl + \underset{\text{Dimethyl urea}}{CH_3.NH.CO.NH.CH_3}$$

(2) Urea is prepared by the synthetic process (first used by Wöhler in 1828) by the intramolecular change which takes place when ammonium cyanate is heated.

$$\underset{\substack{\text{Ammonium}\\ \text{cyanate}}}{NH_4CNO} = \underset{\text{Urea}}{CO(NH_2)_2}$$

A solution containing ammonium sulphate and potassium cyanate is evaporated. Ammonium cyanate is formed and is immediately converted into urea.

$$2KCNO + (NH_4)_2SO_4 = K_2SO_4 + 2NH_4CNO$$

The urea is separated from the potassium sulphate by extracting it in alcohol. The alcoholic solution is evaporated, and the urea is purified by recrystallization from alcohol.

Alkyl derivatives of urea can be obtained by similar reactions from amine salts of cyanic acid.

$$\underset{\substack{\text{Methylammonium}\\ \text{cyanate}}}{CH_3NH_3CNO} = \underset{\text{Methyl urea}}{NH_2.CO.NH.CH_3}$$

(3) Urea can also be obtained by the removal of water from ammonium carbamate, or by the direct reaction of carbon dioxide and ammonia at 150°C under pressure.

$$NH_2.COONH_4 = CO(NH_2)_2 + H_2O$$

$$2NH_3 + CO_2 = CO(NH_2)_2 + H_2O$$

### PROPERTIES OF UREA

Urea crystallizes in colourless prisms melting at 132°C, above which temperature it decomposes, and ammonia is evolved. The molten mass resolidifies owing to the formation of *biuret* (m.p. 190°C). Biuret gives a violet colour on addition of copper sulphate and alkali.

$$\begin{aligned} NH_2.CO.NH_2 &+ NH_2.CO.NH_2 \\ &= NH_3 + \underset{\text{Biuret}}{NH_2.CO.NH.CO.NH_2} \end{aligned}$$

Urea gives the reactions characteristic of acid amides, e.g. it is hydrolyzed to ammonia and a carbonate by alkalis, and it reacts with nitrous acid evolving nitrogen and carbon dioxide.

$$CO(NH_2)_2 + 2NaOH = Na_2CO_3 + 2NH_3$$
$$CO(NH_2)_2 + 2HNO_2 = 2N_2 + CO_2 + 3H_2O$$

Urea also behaves as a mono-acid base and forms salts with acids (the formula indicates the presence of an amino group and an amido group). Of these salts the nitrate $[CO(NH_2)_2, HNO_3]$ and oxalate $[2CO(NH_2)_2, H_2C_2O_4, H_2O]$ are not very soluble in water, and are precipitated from fairly concentrated aqueous solutions of urea on the addition of the corresponding acids.

### DETERMINATION OF UREA

The determination of urea in urine and other biological fluids is of special importance. The following methods are used —

(1) By oxidation with an alkaline solution of sodium hypobromite, prepared by the addition of bromine to sodium hydroxide solution. Nitrogen is set free as a gas, the volume of which is measured. The experiment is carried out in a nitrometer.

$$CO(NH_2)_2 + 3O = N_2 + CO_2 + 2H_2O$$

(2) By hydrolysis to ammonia. An enzyme (urease) present in the soya bean hydrolyzes the urea (in neutral solution) into ammonia.

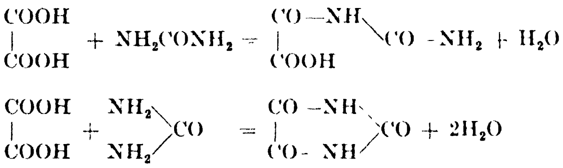
The hydrolysis is carried out by mixing with the ground beans and allowing to stand at 40°C. A current of ammonia-free air is drawn continuously through the mixture to remove the ammonia formed which is then absorbed in an excess of standard acid. The excess acid is determined by titration.

## Derivatives of Urea

Urea reacts with acid chlorides (less readily with the corresponding acids) to form the acyl derivatives of urea, e.g. with acetyl chloride, acetylurea is obtained.

$$CH_3.COCl + NH_2CONH_2 = HCl + \underset{\text{Acetylurea}}{CH_3.CO.NH.CO.NH_2}$$

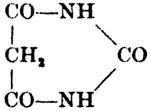
With the dibasic acids, the corresponding urea derivatives can be obtained by reaction with either one or both of the carboxyl groups. Thus with oxalic acid two derivatives are possible.



THE UREIDES

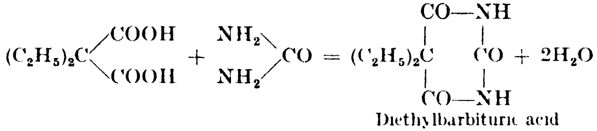
Of these two classes of compounds the derivatives obtained by union with both carboxyl groups are the more important. The molecules of these derivatives contain a closed ring.

These di-urea derivatives of the dibasic acids are called the *ureides*, the most important member being obtained from malonic acid. Malonyl urea (barbituric acid) has the formula

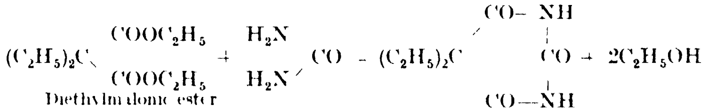


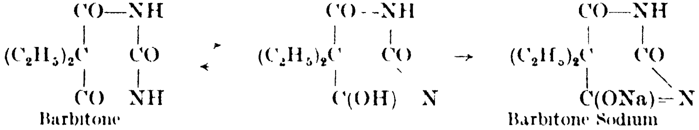
Malonyl urea, barbituric acid

When the diethyl derivative of malonic acid (p. 412) is caused to combine with urea (by reaction in presence of phosphorus oxychloride which helps in the removal of water) diethylbarbituric acid (barbitone) is obtained.

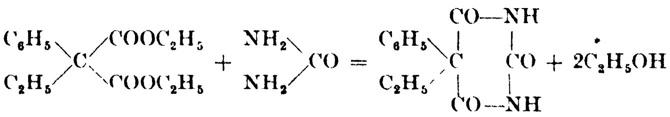


*Barbitone* is usually prepared from the ester of diethylmalonic acid, by condensation with urea in the presence of sodium ethoxide. Under these conditions the sodium salt of barbitone (Soluble Barbitone) is obtained. (This salt is formed after a migration of a hydrogen atom from nitrogen to oxygen, cf. tautomerism p. 471.)

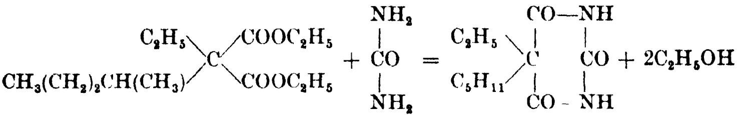




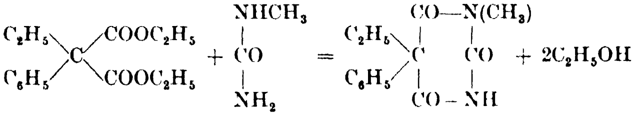
The corresponding phenyl ethyl derivative of malonic acid reacts with urea in a similar manner, and gives the corresponding phenylethylbarbituric acid (Phenobarbitone).



The other barbitone derivatives can be prepared correspondingly, e.g.—*Pentobarbitone* from urea and pentylethylmalonic ester and *Methylphenobarbitone* from methyl urea and phenylethylmalonic ester.

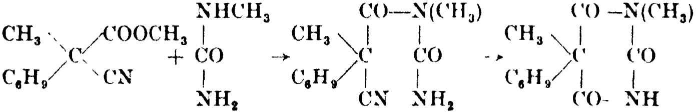


Pentobarbitone



Methylphenobarbitone

*Hexobarbitone* is more conveniently obtained from a cyanacetic ester derivative followed, after condensation with methyl urea, by a hydrolysis which completes the conversion to the malonic acid derivative (cf. preparation of malonic acid itself from cyanacetic acid, p. 412).



Methyl cyclohexenyl cyanacetic ester

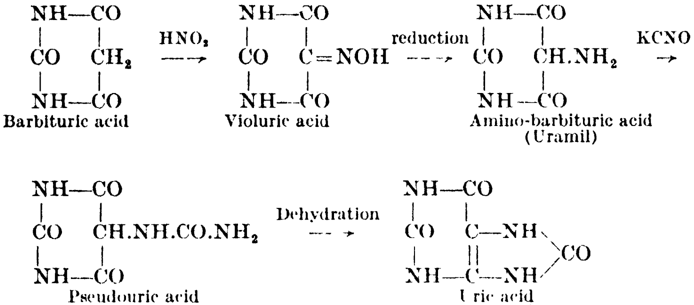
Hexobarbitone

The ureides are crystalline substances, which have acidic properties. The sodium salts are soluble in water; the acids are only sparingly soluble in water, but more soluble in ether. The official sodium salts are assayed by adding dilute hydrochloric acid, extracting the liberated barbituric acid derivatives with ether and weighing them.

## THE PURINES

The cyclic ureides are related to purine and its derivatives, the most important of which are xanthine, caffeine, theobromine, theophylline and uric acid.

*Uric acid* is a diureide and can be obtained from barbituric acid by the following sequence of reactions.



Barbituric acid

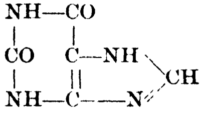
Violuric acid

Amino-barbituric acid (Uramil)

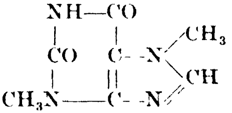
Pseudouric acid

Uric acid

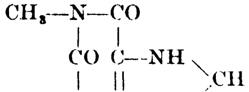
*Xanthine* is closely related to uric acid. *Theobromine* and *theophylline* are dimethyl derivatives of xanthine, while *caffeine* is the trimethyl derivative of xanthine.



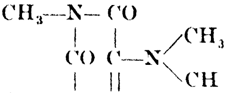
Xanthine



Dimethylxanthine
theobromine



Dimethylxanthine
theophylline

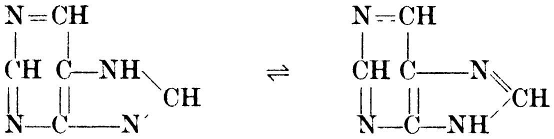


Trimethylxanthine
caffeine

By further methylation, theobromine and theophylline are converted into caffeine. In the official assay of these substances in Theobromine and Sodium Salicylate and in Theophylline and Sodium Acetate, they are converted into and weighed as caffeine. The methylation is carried out by dimethyl sulphate in alkaline solution.

$$(CH_3)_2SO_4 + RH = CH_3HSO_4 + RCH_3$$

Purine from which these compounds are derived has the formula



## THE AMINO-ACIDS AND THE PROTEINS

Amino-acids contain an amino group and a carboxyl group. Consequently their properties are a combination of those of acids and bases, and they form two classes of salts (*a*) with bases, e.g.

$$NH_2.CH_2.COONa$$

(*b*) with acids, e.g.

$$HCl.NH_2.CH_2.COOH$$

The properties vary slightly according to the relative positions of the amino group and the acidic radical, and $\alpha$, $\beta$, $\gamma$ and $\delta$ amino-acids are distinguished.

$$CH_3.CH(NH_2).COOH$$
$\alpha$ aminopropionic acid

$$NH_2CH_2.CH_2.COOH$$
$\beta$ aminopropionic acid

$$NH_2CH_2.CH_2.CH_2.COOH$$
$\gamma$ aminobutyric acid

The $\alpha$ amino-acids are the most important, for when proteins are hydrolyzed they are converted into a mixture of $\alpha$ amino-acids. In the animal body, proteins are hydrolyzed by the enzymes present in the digestive juices.

### Methods of Preparation of Amino-acids

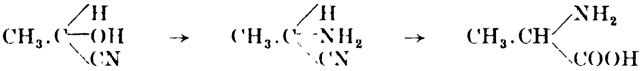
Most of the commoner amino-acids are prepared by the hydrolysis of proteins in acid or alkaline solution.

Amino-acids can be prepared synthetically by modification of the general methods for the formation of amino and acidic compounds.

(1) Amino-acids are prepared from the halogen substituted acids by reaction with ammonia, e.g. monochloracetic acid yields amino-acetic acid (better known as glycine or glycocoll).

$$CH_2Cl.COOH + NH_3 = NH_2CH_2.COOH + HCl$$

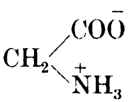
(2) By reacting with ammonia on an aldehyde-cyanhydrin and hydrolyzing the product, an α amino-acid is obtained.



$$CH_3.C\begin{array}{l}/H\\-OH\\\backslash CN\end{array} \rightarrow CH_3.C\begin{array}{l}/H\\-NH_2\\\backslash CN\end{array} \rightarrow CH_3.CH\begin{array}{l}/NH_2\\\backslash COOH\end{array}$$

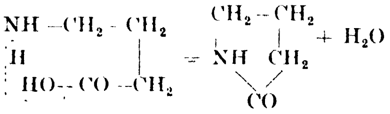
## Properties of Amino-acids

The amino-acids are crystalline compounds, soluble in water and insoluble in organic solvents. These characteristics are those of salt-like bodies, and it is suggested that the amino-acids crystallize in the form of internal salts by the union of the basic and acidic radicals within their molecules. Thus the formula of glycine is probably



$$CH_2\begin{array}{l}/COO^-\\\backslash \overset{+}{N}H_3\end{array}$$

In the case of γ and δ amino-acids, the union between the amino and acidic radicals takes place with loss of water and *lactams* are formed. These compounds which correspond to the lactones of the hydroxy acids indicate the ease of formation of closed ring compounds if the reacting groups are separated by a suitable distance.

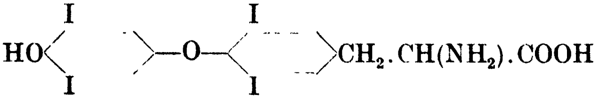


Lactam

*Amino-acetic Acid* (glycine or glycocoll) ($NH_2CH_2.COOH$) is obtained by the hydrolysis of gelatin or glue.

*Alanine* (α aminopropionic acid) ($CH_3.CH(NH_2).COOH$) is formed during the hydrolysis of silk.

*Thyroxine* is a derivative of alanine of the formula



## Proteins and Polypeptides

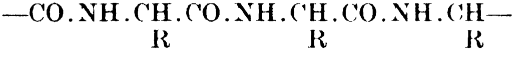
The proteins are biological products, of high molecular weight and colloidal nature. (A few have been obtained in a crystalline state.) On hydrolysis, proteins yield a mixture of various simpler substances, the final products being α amino-acids. Proteins are formed by the combination of amino-acid residues. E. Fischer prepared synthetic substances by the union of eighteen amino-acid molecules, and found that these products resembled to some extent the natural proteins, although the latter were much more complex.

Fischer's experiments indicated that in the proteins the amino-acids are linked between the amino and the carboxyl groups, e.g.

$$\mathrm{NH_2CH_2.CO\,OH\quad H\,NHCH_2.CO\,OH\quad H\,NHCH_2.COOH}$$

$$\rightarrow \mathrm{NH_2CH_2.CO.NH.CH_2.CO.NH.CH_2.COOH}$$

The formula of proteins can therefore be represented as containing a chain of nitrogen and carbon atoms united as follows—



$$\mathrm{—CO.NH.}\underset{\mathrm{R}}{\mathrm{CH}}\mathrm{.CO.NH.}\underset{\mathrm{R}}{\mathrm{CH}}\mathrm{.CO.NH.}\underset{\mathrm{R}}{\mathrm{CH}}\mathrm{—}$$

The presence of these chains in keratin (the protein substance of animal hairs and silk fibres) has been confirmed by X-ray examination. Parallel arrangements of these chains form fibrous structures.

At one end of the protein chain there is an uncombined amino group while at the other end there is an uncombined carboxyl group. Consequently proteins have both acidic and basic properties, and form salts with either acids or alkalis. Such substances are called *amphoteric electrolytes*. The properties of amphoteric electrolytes, e.g. proteins, vary considerably with the $p$H of the solution. (Fig. 29.)

In acid solutions, the protein exists as the salt of the acid. In alkaline solutions, it exists as the salt of the alkali. At a certain intermediate $p$H (known as the *isoelectric point*) the protein exists chiefly in the uncombined state (in the case of gelatin at $p$H 4·7). The variation of the properties of the proteins depends on these changes.

Proteins are often coagulated and rendered insoluble by heating. The coagulation is irreversible, for the precipitated protein is not redispersed on cooling (e.g. egg albumin).

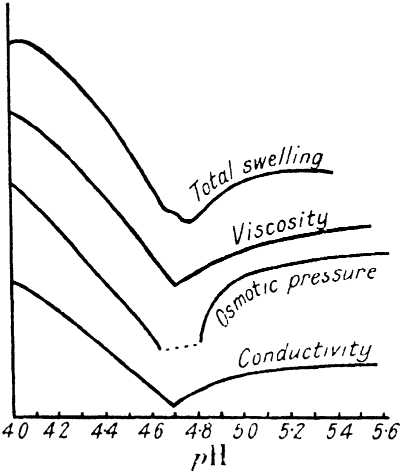


FIG. 29 PROPERTIES OF GELATIN SOLUTIONS

The molecular weights and isoelectric points of some typical proteins are shown in the following table.

TABLE XI

| Protein | Source | Molecular Weight | Isoelectric Point |
|---|---|---|---|
| Egg albumin | Egg-white | 34,500 | pH 4·8 |
| Insulin | Pancreas | 35,000 | 5·6 |
| Haemoglobin | Blood | 66,800 | 6·8 |
| Serum albumin | Blood | 68,000 | 4·7 |
| Serum globulin | Blood | 103,000 | 5·4 |
| Casein | Milk | 375,000 | 4·7 |

## THE ALIPHATIC SULPHUR COMPOUNDS

The oxygen in some organic compounds may be replaced by divalent sulphur, e.g.

$C_2H_5OH \rightarrow C_2H_5SH$ $(C_2H_5)_2O \rightarrow (C_2H_5)_2S$

The sulphur compounds corresponding to the alcohols are called thio-alcohols or mercaptans; the compounds corresponding to the ethers are called thio-ethers.

*The Thio-alcohols* may be prepared from the alkyl halides by reaction with potassium hydrogen sulphide.

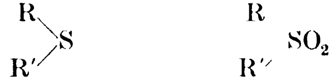
$$C_2H_5Cl + KHS = C_2H_5SH + KCl$$

They are fairly reactive substances which possess characteristic smells.

The *Thio-ethers* are obtained by the reaction of alkyl halides and potassium sulphide.

$$2(C_2H_5)Cl + K_2S = (C_2H_5)_2S + 2KCl$$

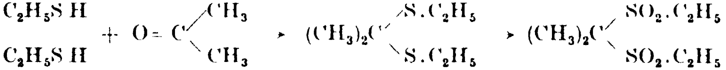
They are oxidized by concentrated nitric acid and by potassium permanganate to *sulphones.*



Thio-ether Sulphone

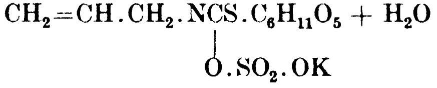
The sulphones are crystalline stable substances.

*Sulphonal* is obtained by the oxidation of the thio-ether prepared by the condensation of acetone with ethyl mercaptan.



Ethyl mercaptan Acetone Sulphonal

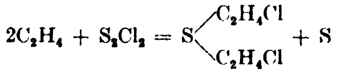
The *Mustard Oils* are esters of isothiocyanic acid (HNCS). Ordinary mustard yields the allyl ester ($CH_2$ $CH.CH_2.NCS$). In the seed these oils exist in the form of a glycoside, which can be hydrolyzed by the enzyme, myrosin, also present in the seed.



$$CH_2{=}CH.CH_2.NCS.\underset{\displaystyle |\atop \displaystyle O.SO_2.OK}{C_6H_{11}O_5} + H_2O$$

$$= C_6H_{12}O_6 + C_3H_5NCS + KHSO_4$$

*Mustard Gas* is a substituted thio-ether obtained by the reaction of sulphur monochloride with ethylene.



$$2C_2H_4 + S_2Cl_2 = S\begin{cases}C_2H_4Cl\\C_2H_4Cl\end{cases} + S$$

*Thio-urea* is prepared from ammonium thiocyanate, as urea is prepared from ammonium cyanate. It is a weak base and is easily hydrolyzed and oxidized. It reacts like urea to form ureide derivatives, e.g. *thiopentone* which is a thiobarbiturate.

$$NH_4CNS = \underset{\text{Thio-urea}}{SC(NH_2)_2}$$

$$SC(NH_2)_2 + 2H_2O = H_2S + CO_2 + 2NH_3$$

$$SC(NH_2)_2 + 4O + H_2O = CO(NH_2)_2 + H_2SO_4$$

*Thioglycollic Acid* is a sensitive reagent for the detection of iron (ferrous or ferric) (cf. iron limit test p. 126). In presence of ammonia a pink or purple colour is developed. The colour is actually formed from ferrous iron but the reagent is able to reduce ferric compounds, being itself readily oxidized to dithiodiglycollic acid $S_2(CH_2.COOH)_2$. Thioglycollic acid can be obtained from chloracetic acid.

$$ClCH_2.COOH + KHS = \underset{\text{Thioglycollic acid}}{HSCH_2.COOH} + KCl$$

# CHAPTER XXVIII

# THE CARBOHYDRATES

THE carbohydrates include substances which contain carbon, hydrogen, and oxygen, the latter two elements being present in the proportion in which they combine to form water (hence the name carbo-hydrates). They are divided into three main classes: (1) the monosaccharide sugars represented by the formula $C_6H_{12}O_6$, (2) the disaccharide sugars of the formula $C_{12}H_{22}O_{11}$, and (3) the higher polysaccharides of the formula $(C_6H_{10}O_5)_n$ where $n$ is a large number. The polysaccharides include such substances as starch and cellulose.

The disaccharides and polysaccharides are derivatives of the simpler monosaccharides. On hydrolysis they are converted into one or more monosaccharide sugars.

$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6$$
$$(C_6H_{10}O_5)_n + nH_2O = nC_6H_{12}O_6$$

## The Monosaccharide Sugars

The monosaccharide sugars have the common formula $C_6H_{12}O_6$. There are a large number of isomers of this formula, many of which occur naturally.

The two most important members of the class are glucose (which is also known as dextrose or as grape sugar) and fructose (which is also known as laevulose or as fruit sugar). The names dextrose and laevulose arose from the sign of their respective optical rotations.

### DERIVATION OF THE STRUCTURAL FORMULA OF GLUCOSE

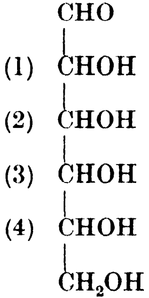
(1) Glucose contains six carbon atoms, which can be proved to be united together to form a straight and unbranched chain, for the reduction of glucose yields a derivative of normal hexane.

(2) Glucose contains five hydroxyl groups as proved by the fact that it reacts with acetyl chloride to give a penta-acetate.

(3) Glucose is a strong reducing agent. It reduces ammoniacal silver nitrate to form a silver mirror, and reduces Fehling's

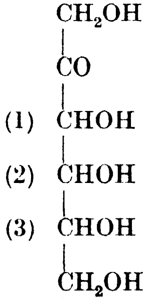
solution to cuprous oxide. The first product of oxidation of glucose is an acid containing the same number of carbon atoms as glucose, and therefore glucose contains an aldehyde group.

These facts lead to the formula for glucose given below. As a result of the study of the corresponding reactions of fructose, it is concluded that this sugar is a ketone.



$$\begin{array}{rl} & \mathrm{CHO} \\ & | \\ (1) & \mathrm{CHOH} \\ & | \\ (2) & \mathrm{CHOH} \\ & | \\ (3) & \mathrm{CHOH} \\ & | \\ (4) & \mathrm{CHOH} \\ & | \\ & \mathrm{CH_2OH} \end{array}$$

Glucose



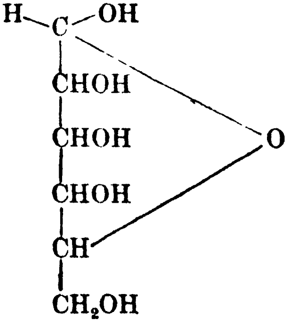
$$\begin{array}{rl} & \mathrm{CH_2OH} \\ & | \\ & \mathrm{CO} \\ & | \\ (1) & \mathrm{CHOH} \\ & | \\ (2) & \mathrm{CHOH} \\ & | \\ (3) & \mathrm{CHOH} \\ & | \\ & \mathrm{CH_2OH} \end{array}$$

Fructose

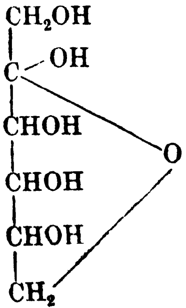
Glucose contains four asymmetric carbon atoms (1, 2, 3, 4) and fructose contains three asymmetric carbon atoms (1, 2, 3).

Owing to stereoisomerism there are sixteen different sugars of the glucose formula, and eight different sugars of the fructose formula. The aldehyde sugars (e.g. glucose) are called *aldoses*, the ketone sugars (e.g. fructose) are called *ketoses*.

The reactions of the monosaccharide sugars are in accordance with the above straight chain formulae. But in the crystalline state, the sugars exist in a closed ring form. Thus glucose and fructose are represented by the formulae

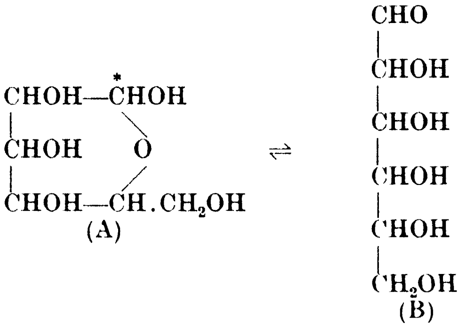


Glucose



Fructose

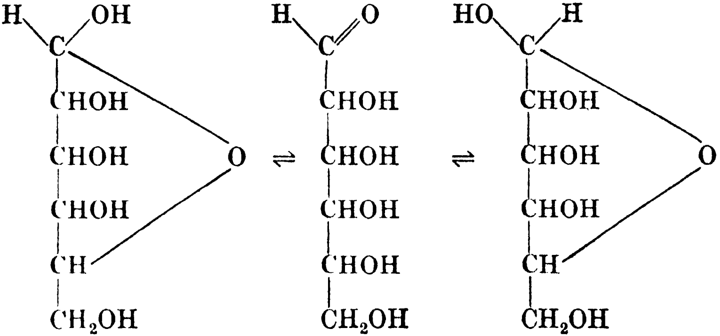
In solution, the closed ring form is partially converted into the straight chain form.



The evidence from which the closed ring formula was deduced was partly by analogy and comparison with the glucosides (p. 458) and partly by the discovery of the *mutarotation* of sugars. When the optical rotation of a pure substance is not constant but changes on standing (more rapidly on boiling, or in the presence of a catalyst), the substance is said to undergo mutarotation. Mutarotation indicates the existence of some change taking place in the solution of the substance. The closed ring formula (A) contains one more asymmetric carbon atom (indicated by an asterisk) than the straight chain formula (B). The conversion of (B) to (A) leads to the formation of two compounds of rotations $D_A + x$, and $L_A + x$ where $x$ represents the optical rotation of B, and $D_A$ and $L_A$ are the rotations of the extra asymmetric atom in A.

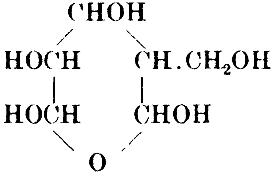
In the case of glucose the two compounds are called α glucose and β glucose. When crystalline glucose (α glucose, optical rotation 105°) is dissolved in water, it begins to change into β glucose (optical rotation 22°) through the intermediate formation of the open chain compound. Therefore the initial optical rotation due to pure α glucose alters slowly, until an equilibrium mixture containing both α and β glucose is obtained (optical rotation 55°). The value of the optical rotation of this mixture is constant, and is used officially to control the purity of Dextrose.

Similarly for other monosaccharide sugars, the optical rotation of the equilibrium mixture can be used to control their purity.

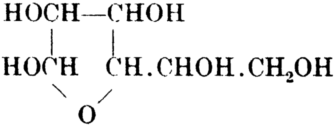


α glucose β glucose

Other modifications of the sugars have been obtained with the ring formed on the next higher carbon atom in the above formula, i.e. forming a five-membered instead of a six-membered ring. These are the γ sugars. An alternative nomenclature relates the sugars to the heterocyclic compounds pyran and furan (p. 559) thus—



Glucose or glucopyranose

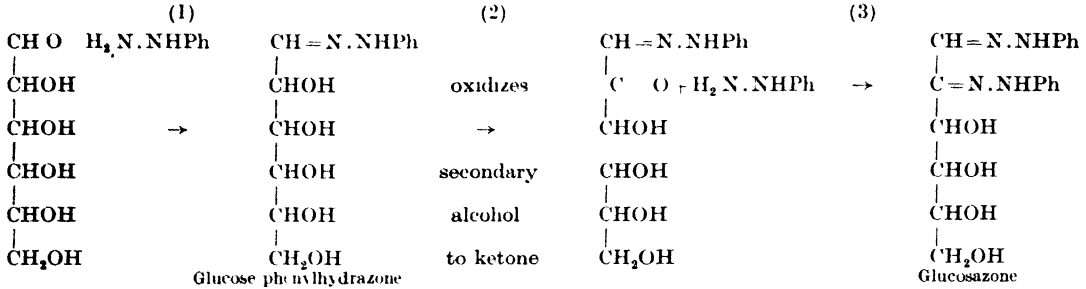


γ-glucose or glucofuranose

## General Properties of the Monosaccharides

The monosaccharides are crystalline, water soluble, and sweet-tasting substances. They give the reactions of alcohols (reacting with acetyl chloride, phosphorus pentachloride, etc.) and of ketones or aldehydes. They are reducing agents, and reduce ammoniacal silver nitrate and Fehling's solution. In the absence of other reducing agents, the reduction of Fehling's solution is used as a method of quantitative determination of these sugars. Certain monosaccharide sugars, e.g. glucose, are fermented by yeast.

With glucose the stages may be represented as follows—

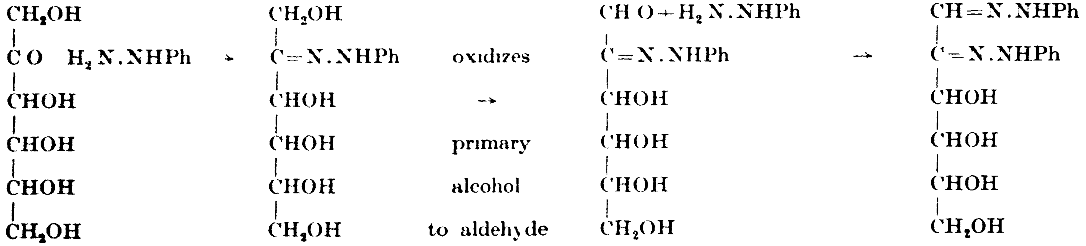


$$\begin{array}{lclclcl}
CHO + H_2N.NHPh & & CH{=}N.NHPh & & CH{=}N.NHPh & & CH{=}N.NHPh \\
| & & | & & | & & | \\
CHOH & & CHOH & \text{oxidizes} & CO + H_2N.NHPh & \rightarrow & C{=}N.NHPh \\
| & & | & & | & & | \\
CHOH & \rightarrow & CHOH & \rightarrow & CHOH & & CHOH \\
| & & | & & | & & | \\
CHOH & & CHOH & \text{secondary} & CHOH & & CHOH \\
| & & | & & | & & | \\
CHOH & & CHOH & \text{alcohol} & CHOH & & CHOH \\
| & & | & & | & & | \\
CH_2OH & & CH_2OH & \text{to ketone} & CH_2OH & & CH_2OH
\end{array}$$

Glucose phenylhydrazone

Glucosazone

and with fructose—



$$\begin{array}{lclclcl}
CH_2OH & & CH_2OH & & CHO + H_2N.NHPh & & CH{=}N.NHPh \\
| & & | & & | & & | \\
CO + H_2N.NHPh & \rightarrow & C{=}N.NHPh & \text{oxidizes} & C{=}N.NHPh & \rightarrow & C{=}N.NHPh \\
| & & | & & | & & | \\
CHOH & & CHOH & \rightarrow & CHOH & & CHOH \\
| & & | & & | & & | \\
CHOH & & CHOH & \text{primary} & CHOH & & CHOH \\
| & & | & & | & & | \\
CHOH & & CHOH & \text{alcohol} & CHOH & & CHOH \\
| & & | & & | & & | \\
CH_2OH & & CH_2OH & \text{to aldehyde} & CH_2OH & & CH_2OH
\end{array}$$

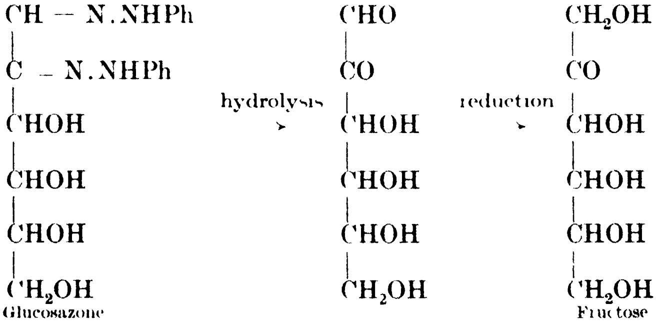
Fructose phenylhydrazone

Fructosazone

Phenyl hydrazine reacts with these sugars in three stages: (1) it reacts with the aldehyde or ketone group, (2) it acts as an oxidizing agent, and oxidizes the alcohol group immediately next to the aldehyde or ketone group, (3) it reacts with the products formed by this oxidation. The final product is an *osazone* (p. 456).

The osazones are sparingly soluble substances, which are often used to separate the sugars from solution in an easily recognizable form. Each osazone has a definite melting point and a characteristic crystal form (when examined under the microscope).

Fructosazone and glucosazone are identical. On hydrolysis and reduction they are both converted into fructose. By forming the osazone, it is possible to convert glucose into fructose.



Concentrated sulphuric acid converts the monosaccharide sugars into derivatives of furfural which react with α naphthol to form violet-coloured compounds. (This reaction is the basis of Molisch's test for carbohydrates.)

*Glucose, Grape Sugar or Dextrose.* [The name glucose is applied by chemists to the pure sugar named in the *British Pharmacopœia* as Dextrose. The official Liquid Glucose (p. 465) contains maltose and dextrin as well as glucose.]

Glucose is found in grapes and other fruits. Honey consists mainly of a mixture in equal proportions of glucose and fructose (invert sugar). Glucose is not assimilated by diabetic patients and is found in considerable quantities in their urine.

Commercially glucose is obtained from starch by hydrolysis with dilute acids. The product is neutralized, sometimes treated with sulphur dioxide to hinder fermentation, filtered through charcoal, and evaporated to crystallization point. Dextrose B.P. consists of anhydrous glucose, but a hydrated form (Dextrose Monohydrate; $C_6H_{12}O_6$, $H_2O$) is also official.

Invert sugar is formed when cane sugar is hydrolyzed (cf. p. 462). The glucose can be separated from the mixture by fractional crystallization from alcohol.

*Fructose or Laevulose* is separated from invert sugar or honey by adding milk of lime. The fructose compound with calcium hydroxide is less soluble than the corresponding glucose compound. After separation the fructose is recovered by decomposition with carbon dioxide. It is very difficult to obtain the pure sugar and the commercial product contains some glucose.

$$C_6H_{12}O_6,\ Ca(OH)_2 + CO_2 = C_6H_{12}O_6 + CaCO_3 + H_2O$$

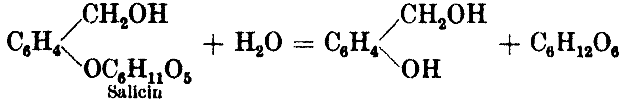
Fructose is formed when inulin (a starch-like substance occurring in the roots and tubers of certain plants, e.g. dahlias) is hydrolyzed.

## THE GLYCOSIDES

The *glucosides* are derivatives of glucose (usually soluble in water) which occur naturally in plants. The name was originally applied also to the similar derivatives of other sugars, but it is usual nowadays to restrict the term glucoside to the derivatives of glucose. The term *glycoside* should be applied more generally.

When glucosides are hydrolyzed (by the catalytic action of acids or enzymes) they form a mixture of glucose and other substances. For example, amygdalin (which is present in bitter almonds) is hydrolyzed by emulsin to benzaldehyde, hydrocyanic acid, and glucose; and salicin (which is present in the bark of poplars and willows) hydrolyzes to salicyl alcohol (p. 517) and glucose.

$$\underset{\text{Amygdalin}}{C_6H_5.CH(CN)\text{—}O\text{—}C_{12}H_{21}O_{10}} + 2H_2O$$
$$= C_6H_5.CHO + HCN + 2C_6H_{12}O_6$$

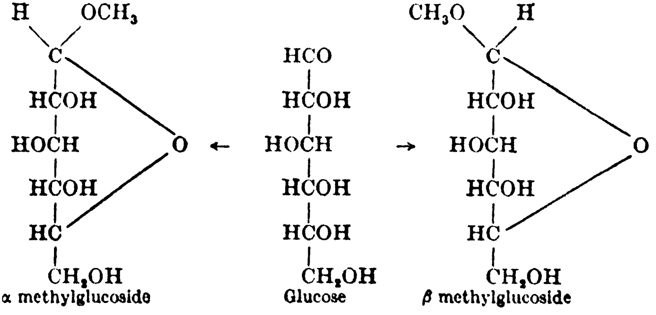


$$\underset{\text{Salicin}}{C_6H_4\left\langle\begin{matrix}CH_2OH\\ OC_6H_{11}O_5\end{matrix}\right.} + H_2O = C_6H_4\left\langle\begin{matrix}CH_2OH\\ OH\end{matrix}\right. + C_6H_{12}O_6$$

Many natural glycosides are considerably more complex than amygdalin and salicin. The glycosides Digoxin and Ouabain are hydrolyzed to glucose and other sugars and residues which are closely related to the sterols (p. 556).

The glucosides are divided into two classes, the α and the β glucosides. These are affected differently by enzymes; some enzymes (e.g. maltase) hydrolyze only the α glucosides, while other enzymes (e.g. emulsin) hydrolyze only β glucosides. Most natural glucosides are β glucosides.

The properties of glucosides resemble those of ethers; they do not possess reducing properties, and therefore contain no aldehyde group. These facts together with the existence of the two types of glucosides led to their representation by a closed ring formula (which contains one more asymmetric carbon atom than the straight chain formula for the sugar itself). For example, glucose reacts with methyl alcohol to form α and β methylglucosides which are represented by the following formulae (which also indicate the relative configurations of the asymmetric carbon atoms).



When the corresponding forms of glucose were isolated, and found to correspond with the two types of glucosides, the ring formulae were applied to the sugars themselves.

### OTHER DERIVATIVES OF THE MONOSACCHARIDES

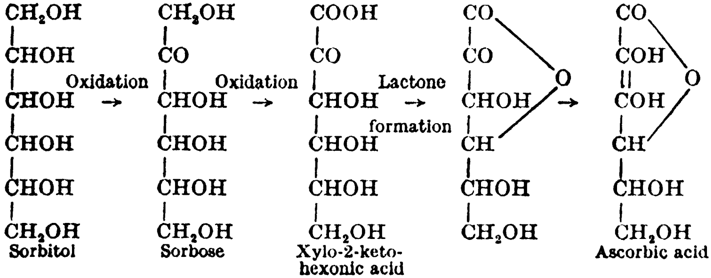
*Gluconic Acid.* Glucose is oxidized by mild oxidizing agents (e.g. bromine water) at the aldehyde group only. The acid formed is called gluconic acid and has the formula $CH_2OH(CHOH)_4COOH$. Its calcium salt is official

$[(CH_2OH(CHOH)_4COO)_2Ca,\ H_2O)]$ and is assayed on its calcium content.

*Ascorbic Acid* (vitamin C) is related to *l*-gulose, one of the stereoisomeric sugars of glucose. It is obtained from various natural sources (lemons, black currants, etc.) and is synthesized from a structurally related alcohol (sorbitol) which occurs in mountain ash berries.

The first stage in the synthetic process is an oxidation to a ketone and this can be effected by the action of certain bacteria. The final conversion of the hexonic acid lactone to ascorbic acid is achieved by heating with dilute acids.

The simplified scheme is as follows—



The acidity of ascorbic acid lies in its C(OH) = C(OH) group (cf. enolic ethyl acetoacetate, p. 471) and its powerful reducing action also lies in that group which is converted by mild oxidizing agents to the —CO—CO—group, forming dehydro-ascorbic acid, from which ascorbic acid can be regenerated. Powerful oxidation breaks up the molecule.

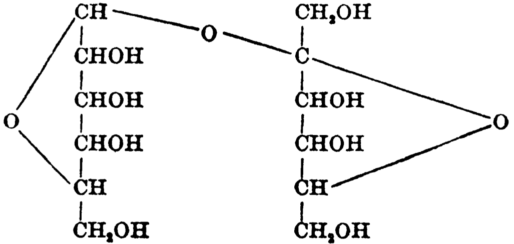
## The Disaccharides

The disaccharides are a group of sweet-tasting soluble sugars of the general formula $C_{12}H_{22}O_{11}$. They correspond to compounds formed by the combination of two molecules of monosaccharides by the elimination of water, and they are easily hydrolyzed to form monosaccharides.

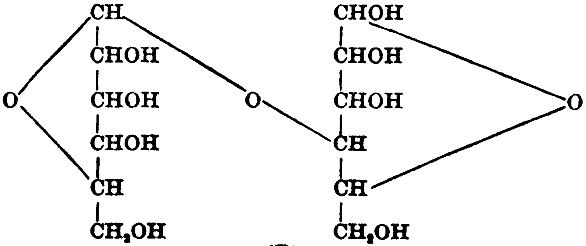
$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6$$

Most disaccharides on hydrolysis yield two different monosaccharides, e.g. sucrose yields glucose and fructose, lactose yields glucose and galactose. Maltose, on the other hand, yields glucose alone. The hydrolysis of the disaccharides may be carried out by acid catalysis, or by enzymes, e.g. diastase, or invertase. The disaccharides must be hydrolyzed prior to alcoholic fermentation.

The linkage between the two monosaccharides is formed by eliminating water between two hydroxyl groups, so that the monosaccharide residues are linked by means of oxygen. If this linkage takes place at the aldehyde or ketone carbon atom, the product will not have reducing properties, e.g. sucrose (A), but if the linkage is formed through other carbon atoms the disaccharide sugar still has reducing properties, e.g. lactose and maltose (B).



(A)



(B)

*Sucrose or Cane Sugar* occurs in the juices of the sugar cane, sugar beet, and other plants, and it is prepared on the large scale from sugar beets and sugar canes.

The sugar is extracted from the sliced beets by diffusion in hot water. The juice is extracted from the sugar canes by crushing them in contact with water by heavy pressure under warm rollers. Lime is added to the crude sugar solutions to remove acid impurities as the insoluble calcium salts, and to coagulate albuminoid matter. This process is called *defecation.*

The lime is removed by passing carbon dioxide into the sugar solution which decomposes the calcium sucrosate formed previously. After filtration, the sugar solution is evaporated *in vacuo* to crystallization point. (More than one treatment with lime and carbon dioxide may be necessary to obtain a pure enough syrup before evaporation.) The first product is slightly yellow, and ultramarine may be added to neutralize the yellow tint. (The official test for ultramarine depends on the reduction of the sulphur present in the colouring matter by means of hypophosphorous acid.) Pure white sugar is obtained by redissolving, and decolorizing the solution by filtration through charcoal.

The sugar in the mother liquor (molasses) may be partly recovered by precipitation as the sparingly soluble compound with strontium hydroxide [$Sr(OH)_2, C_{12}H_{22}O_{11}$]. Alternatively the molasses may be converted into alcohol by fermentation.

Cane sugar forms characteristic crystals which on melting and resolidifying set to glassy "barley sugar." On further heating, decomposition takes place and caramel is formed.

Cane sugar on hydrolysis forms a mixture of glucose and fructose. Although the fructose exists as a $\gamma$ ring sugar in the sucrose molecule, the product of hydrolysis is the normal ring sugar following upon a molecular rearrangement.

$$\underset{\text{Sucrose}}{C_{12}H_{22}O_{11}} + H_2O = \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Fructose}}{C_6H_{12}O_6}$$

The laevo-rotation of fructose $[-81°]^{20° C}$ is greater than the dextro-rotation of glucose $[+52°]^{20° C}$, so that on hydrolysis the dextro-rotatory solution of sucrose $[+66{\cdot}5°]^{20° C}$ becomes laevo-rotatory $[-29°]^{20° C}$. For this reason this hydrolysis is commonly known as the *inversion* of cane sugar, and the product is called *invert sugar.*

(The inversion of sugar forms the basis of its quantitative determination by polarimetric examination).

Although sucrose does not possess reducing properties, the sugars formed after it has been hydrolyzed do possess reducing properties.

When sucrose is hydrolyzed, using inorganic acids as catalysts, a small quantity becomes converted into furfural, and the presence of this substance enables the addition of artificial invert sugar to honey to be detected.

*Lactose or Milk Sugar* is found in the milk of mammals. It is prepared from whey, which is a by-product of the manufacture of cheese. The sugar is extracted from the whey by adding dilute acetic acid to precipitate the albuminoids which are removed by filtration. The lactose is obtained by evaporation *in vacuo*, and is purified by treatment with charcoal and recrystallization.

Lactose is a dextro-rotatory sugar, which forms a white crystalline powder. It is less sweet than sucrose. The normal form of lactose is hydrated $\alpha$ lactose [$C_{12}H_{22}O_{11}$, $H_2O$], but anhydrous $\alpha$ lactose and $\beta$ lactose can also be obtained.

Lactose is a reducing sugar (cf. formula, p. 461). It yields a mixture of galactose and glucose on hydrolysis.

$$\underset{\text{Lactose}}{C_{12}H_{22}O_{11}} + H_2O = \underset{\text{Galactose}}{C_6H_{12}O_6} + \underset{\text{Glucose}}{C_6H_{12}O_6}$$

Lactose readily undergoes the lactic fermentation with the formation of lactic acid. This reaction takes place during the souring of milk.

$$C_{12}H_{22}O_{11} + H_2O \quad 4CH_3.CHOH.COOH$$

*Maltose* is produced by the gentle hydrolysis of starch, e.g. by the action of the diastase produced during the germination of barley (p. 357). Maltose is a reducing sugar, which on hydrolysis yields glucose. Maltose is not fermentable by yeast unless first hydrolyzed to glucose.

$$\underset{\text{Maltose}}{C_{12}H_{22}O_{11}} + H_2O = \underset{\text{Glucose}}{2C_6H_{12}O_6}$$

## The Polysaccharides

These complex higher carbohydrates (e.g. cellulose, starch, glycogen, and inulin) are usually represented by the formula $(C_6H_{10}O_5)_n$ where $n$ is a large number. The more important are cellulose and starch. The polysaccharides are insoluble amorphous substances which are hydrolyzed by acids or by enzyme action into simpler monosaccharides.

$$(C_6H_{10}O_5)_n + nH_2O = nC_6H_{12}O_6$$

They are formed therefore by the union of simpler monosaccharide groupings by linkages involving the elimination of water as in the formation of the disaccharides.

## STARCH

Starch is a substance which occurs very widely in the vegetable kingdom, where it serves as a store of carbohydrate food in seeds (e.g. the grain of wheat, maize, and rice), and in tubers (e.g. potatoes). The starch is stored in granules which, when seen under the microscope, have characteristic appearances which, in general, enable the source of the starch to be identified. The material forming the wall of the starch grain is probably different from that occupying the interior.

Starch is obtained commercially from maize, rice, or other cereals and from potatoes. When the raw material is disintegrated and washed with water the starch granules pass into a suspension, which is then filtered using a filter of such a size that only the starch grains pass through. After settling and further purification, the starch grains are washed with water, separated in a centrifuge, and dried slowly.

Starch is a white amorphous powder, which is insoluble in water. On heating with water the starch granules burst and starch paste is formed. Starch paste when cold forms an intense blue-coloured compound with iodine, which decomposes on heating. The formation of the blue colour with starch paste enables small quantities of iodine to be detected.

Starch is not a reducing substance so that the glucose residues are linked in starch through the aldehyde carbon atom (probably by an $\alpha$ glucosidic linkage as in maltose). Starch can be chemically divided into two portions—amylose in which the 50 to 250 glucose residues are more or less in a straight line, and amylopectin, which contains a much greater number of glucose residues not wholly arranged in a straight line. The two constituents are not in the same proportion throughout the starch grain, e.g. there is a greater concentration of amylose in the interior.

When starch is hydrolyzed by acids, or the enzyme diastase, simpler products are formed. The first product is a gummy substance, known as dextrin or British gum. A second stage (as by the action of the enzyme diastase) yields maltose.

$$\underset{\text{Starch}}{2(C_6H_{10}O_5)_n} + nH_2O = \underset{\text{Maltose}}{nC_{12}H_{22}O_{11}}$$

The final product of hydrolysis is glucose.

$$(C_6H_{10}O_5)_n + nH_2O = nC_6H_{12}O_6$$

*Liquid Glucose B.P.* is obtained by the partial hydrolysis of starch by dilute acids, and consists of a mixture of glucose, maltose, dextrin, and water.

Sulphur dioxide is used to hinder fermentation during the evaporation of the sugar solution. There is an official limit of sulphur dioxide in Liquid Glucose. The sulphur dioxide is removed by passing a current of carbon dioxide through a boiling acidified solution of the substance. The stream of gas is passed through a solution of hydrogen peroxide, previously neutralized to bromophenol blue. (The $p$H of this solution corresponds to that of a saturated solution of carbon dioxide, so that it is not altered by absorption of this gas.) The sulphur dioxide reacts with the hydrogen peroxide, forming sulphuric acid, which is determined by titration with standard alkali.

$$H_2O_2 + SO_2 = H_2SO_4$$

Soluble starch is obtained by a treatment with acid insufficient to cause appreciable hydrolysis.

### CELLULOSE

Cellulose is the complex polysaccharide which forms the cell-walls of plants. Empirically the formula of cellulose is $(C_6H_{10}O_5)_n$, where $n$ is a large number (100 to 200).

Cellulose is obtained from many plant products (e.g. wood, cotton, flax, hemp, etc.). To obtain pure cellulose the other substances present in the plant material (e.g. cotton wool) are removed by treatment with various solvents, e.g. water, acids and alkalis, alcohol and ether. Cellulose remains in the form of a white amorphous mass. The finest filter-papers consist of almost pure cellulose, while ordinary paper, cotton, and linen fabrics consist mainly of cellulose.

### *Properties of Cellulose*

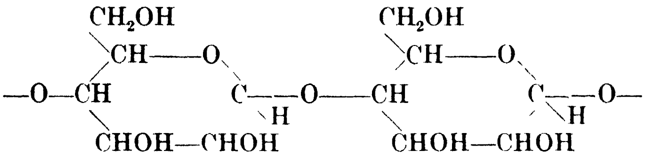
Cellulose is not soluble in the usual reagents, but can be dissolved by "*Schweitzer's* reagent" (a solution of copper hydroxide in ammonia which contains cuprammonium hydroxide), and by the use of carbon disulphide in alkaline solution. These reagents are used as solvents in the manufacture of artificial silk.

Cellulose on hydrolysis breaks down into simpler products, the more important of which are a disaccharide sugar ($C_{12}H_{22}O_{11}$) called cellobiose, and the product of the further hydrolysis of this disaccharide, which is glucose.

$$\underset{\text{Cellulose}}{2(C_6H_{10}O_5)_n} + nH_2O = \underset{\text{Cellobiose}}{nC_{12}H_{22}O_{11}}$$

$$\underset{\text{Cellobiose}}{C_{12}H_{22}O_{11}} + H_2O = \underset{\text{Glucose}}{2C_6H_{12}O_6}$$

In cellobiose one glucose residue is linked to the other by a $\beta$ glucoside linkage, and it is concluded that cellulose contains a large number of glucose units in this way.



Under these circumstances, the glucose residues form a straight chain, and thus the cellulose molecule consisting of a large number of these residues takes on a thread-like structure. The cellulose fibre consists of bundles of cellulose molecules arranged parallel with one another with their long axes pointing along the length of the fibre.

Starch, like cellulose, contains glucose residues, but they are linked by $\alpha$ glucosidic linkages. The successive units then do not lie in a straight line, and starch does not possess a fibrillar structure.

### *Esters of Cellulose*

Cellulose, like other carbohydrates, contains several hydroxyl groups, and its formula can be represented by $[C_6H_7O_2(OH)_3]_n$. The hydroxyl groups of cellulose give rise to esters by interaction with acids. These esters are of considerable commercial importance, the nitric esters being used as explosives and for the manufacture of collodion, celluloid (by addition of camphor) and cellulose varnishes. Cellulose acetates are used for the manufacture of artificial silk and non-inflammable films and varnishes.

The *cellulose nitrates* (or nitrocelluloses, as they are less accurately called) are obtained by the reaction of nitric and sulphuric acids on cellulose. The number of hydroxyl groups which are esterified depends on the length of time treated and the strength of the acids, and the products vary from the mono-nitrate $[C_6H_7O_2NO_3(OH)_2]_n$ to the fully nitrated trinitrate $[C_6H_7O_2(NO_3)_3]_n$ obtained by using the strongest acids. It is not practicable to isolate any one of these products, as a mixture is always obtained.

The medium nitric esters of cellulose, e g. Pyroxylin, which consists chiefly of $[C_6H_7O_2(NO_3)_2OH]_n$ are inflammable substances which dissolve more readily than cellulose. When brought into contact with solvents such as acetone or ethyl acetate, they swell up and pass into solution. A solution in alcohol-ether is known as collodion. The degree of nitration of Pyroxylin is controlled officially by the viscosity of a 3 per cent solution in acetone (p. 111).

The medium nitrates of cellulose when mixed with camphor and heated form celluloid.

On further nitration, the esters of cellulose become more explosive, the highest nitrated ester being known as gun-cotton. Gun-cotton is obtained by treatment of carefully washed cotton with a mixture of the strongest sulphuric and nitric acids. The product is washed free from acids. It burns very readily and on detonation is a powerful explosive, which is used either alone, or mixed with nitroglycerin in the form of blasting gelatine, and smokeless powders. Gun-cotton is insoluble in alcohol-ether.

*Cellulose Acetates.* The acetic acid esters of cellulose can be obtained by treatment of cellulose with acetic acid, acetyl chloride, or acetic anhydride. As in the case of the nitric esters, cellulose forms mono-, di-, or tri-acetates.

## CHAPTER XXIX

# SYNTHETIC PROCESSES IN ORGANIC CHEMISTRY

After the molecular formula of any organic substance has been determined (cf. p. 13), its constitution is deduced from its reactions, and from the nature of the simpler substances obtained when the compound is broken down.

Having arrived at a possible composition of the compound by breaking it down (*analysis*), the composition is confirmed by preparing synthetically the compound which possesses this composition. Comparison is then made with the original substance. *Synthesis* is the process of building up a compound from its constituent elements, or from simpler compounds which in their turn can be built up from their elements.

There are several standard methods and reagents which are suitable for synthesizing the more complex organic compounds, but any of the reactions mentioned previously for the preparation of the different classes of organic compounds may be adapted for synthetic purposes. Typical syntheses of some simpler organic compounds are represented on p. 469.

### Ascent of a Homologous Series

The formation of a cyanide and its subsequent hydrolysis gives a compound containing an additional carbon atom in the molecule. A complete series of reactions, based on this reaction, for the ascent of a homologous series is represented as follows—

$$CH_3OH \rightarrow CH_3I \rightarrow CH_3CN \rightarrow CH_3.COOH$$
$$\rightarrow CH_3.CHO \rightarrow C_2H_5OH$$

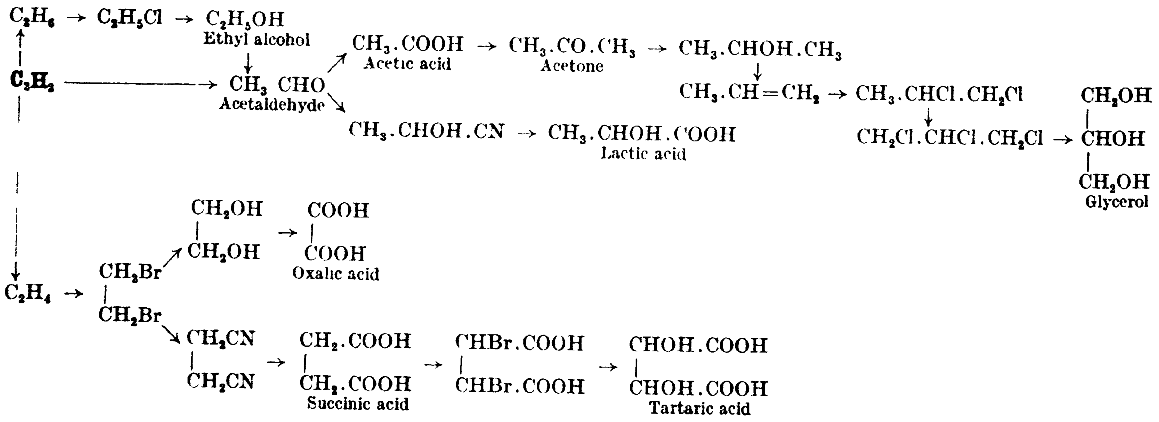
### Descent of a Homologous Series

The reaction by which acid amides are converted into amines with one atom of carbon less in their molecules is the basis of a useful method of descending a homologous series.

A complete series of reactions may be represented as follows—

$$CH_3.COOH \rightarrow CH_3.COONH_4 \rightarrow CH_3.CONH_2$$
$$\rightarrow CH_3NH_2 \rightarrow CH_3OH \rightarrow HCOOH$$

$$C + 2H_2 = CH_4$$
$$2C + H_2 = C_2H_2$$
$$CO + 2H_2 = CH_3OH$$
$$CO + NaOH = HCOONa$$
$$CH_4 \rightarrow CH_3Cl \rightarrow \underset{\text{Methyl alcohol}}{CH_3OH} \rightarrow \underset{\text{Formaldehyde}}{HCHO} \rightarrow \underset{\text{Formic acid}}{HCOOH}$$



Another reaction which may be utilized for the descent of a homologous series is the conversion of a sodium salt of a fatty acid into a hydrocarbon with one fewer carbon atom in its molecule by heating with soda-lime. A complete series may be represented as follows—

$$C_2H_6 \rightarrow C_2H_5Cl \rightarrow C_2H_5OH \rightarrow CH_3.COOH \rightarrow CH_4$$

## Synthesis of Acids and Ketones by means of Aceto-acetic Ester

*Aceto-acetic Ester* is the (ethyl) ester of the acid obtained by replacing one of the hydrogen atoms of acetic acid by the acetyl group.

$$\underset{\text{Acetic acid}}{CH_3.COOH} \qquad \underset{\text{Aceto-acetic acid}}{CH_3.CO.CH_2.COOH}$$

$$\underset{\text{Ethyl aceto-acetate or aceto-acetic ester}}{CH_3.CO.CH_2.COOC_2H_5}$$

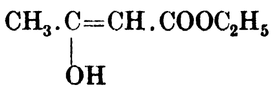
The free acid is not known.

Ethyl aceto-acetate is prepared by the action of sodium on dry ethyl acetate. The reaction is complex. It starts slowly and gradually builds up to a vigorous reaction. The final result of the reaction may be represented by the equation

$$2CH_3.COOC_2H_5 + 2HCH_2.COOC_2H_5 + 2Na$$
$$= 2CH_3.CO.CH_2.COOC_2H_5 + 2C_2H_5ONa + H_2$$

*Tautomerism of Aceto-acetic Ester.* Ethyl aceto-acetate is a sweet-smelling liquid, which is very reactive. For many years its reactions were difficult to explain, as it seemed to behave as if it possessed two distinct constitutions. In accordance with the formula given above it behaves as a ketone, and forms a phenylhydrazone, which is used for the preparation of phenazone and amidopyrine (cf. p. 564).

The ketone formula also explains the products obtained when ethyl aceto-acetate is hydrolyzed. But ethyl aceto-acetate also gives a colour with ferric chloride (normally indicative of the presence of a hydroxyl group in the molecule), and it reacts with sodium evolving hydrogen. These reactions can be interpreted by the formula



$$CH_3.\underset{\displaystyle OH}{\underset{|}{C}}{=}CH.COOC_2H_5$$

It was found that aceto-acetic ester consists of two distinct substances, which are so easily interconverted by the *migration* of a hydrogen atom that a state of chemical equilibrium is attained.

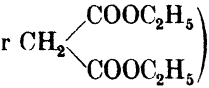
$$\underset{\text{Ketonic form}}{CH_3.CO.CH_2.COOC_2H_5} \rightleftharpoons \underset{\text{Enolic form}}{CH_3.C(OH)=CH.COOC_2H_5}$$

Ordinary aceto-acetic ester is a mixture containing both the *ketonic* form (containing the ketone group) and the *enolic* form (*en* = ethylenic linkage, *ol* = hydroxyl group). In keeping with the normal properties of equilibrium mixtures, as the one form is removed in the form of a derivative, the equilibrium is adjusted until the whole of the ethyl aceto-acetate is converted into the derivative of that one form.

With extreme precautions of cleanliness, the two forms of aceto-acetic ester may be separated. But as soon as the minutest traces of catalysts (e.g. dust particles) are introduced, interconversion proceeds rapidly, and either form quickly reverts to the ordinary equilibrium mixture.

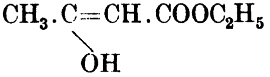
When two distinct isomers are so easily interconverted that only one substance is ordinarily obtained (which is an equilibrium mixture containing both forms), the type of isomerism is called *dynamic isomerism*, or *tautomerism*. The two forms are called dynamic isomers or tautomers.

Dynamic isomerism is found among more than one class of substance. The class (as in aceto-acetic ester) where dynamic isomerism takes place between a ketone and an unsaturated alcohol is commonly called keto-enol isomerism. Other types are represented by the purine derivatives (p. 443) and by hydrogen cyanide (p. 230).

Keto-enol isomerism is found in those compounds which contain a carbon atom (united to one or two hydrogen atoms) placed between a carbonyl group and an ester group (as in aceto-acetic ester), or between two carbonyl groups (as in acetylacetone $CH_3.CO.CH_2.CO.CH_3$) or two ester groups (as in malonic ester  $CH_2\begin{matrix}\diagup COOC_2H_5\\ \diagdown COOC_2H_5\end{matrix}$).

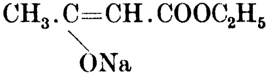
The importance of aceto-acetic ester in synthetic organic chemistry is closely connected with its tautomeric properties.

When it reacts with sodium, a derivative of the enolic form is obtained, which reacts with alkyl halides to form an alkyl derivative of aceto-acetic ester, in which one of the central hydrogen atoms of the aceto-acetic ester is replaced by an alkyl group.



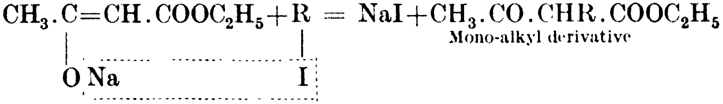
$CH_3.\underset{OH}{C}=CH.COOC_2H_5$

Aceto-acetic ester



$CH_3.\underset{ONa}{C}=CH.COOC_2H_5$

Sodium derivative



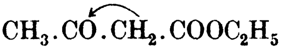
$CH_3.\underset{ONa}{C}=CH.COOC_2H_5+\underset{I}{R} = NaI+CH_3.CO.CHR.COOC_2H_5$

Mono-alkyl derivative

The mono-alkyl derivatives of aceto-acetic ester are tautomeric.

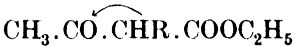
$$CH_3.CO.CHR.COOC_2H_5 \rightleftharpoons CH_3.C(OH)=CR.COOC_2H_5$$

By forming the sodium derivative and reacting with an alkyl halide, a di-alkyl derivative of aceto-acetic ester is obtained. The di-alkyl derivatives are not tautomeric, since the central carbon atom is no longer united to hydrogen atoms.



$CH_3.\overset{\frown}{CO.CH_2}.COOC_2H_5$

Ethyl aceto-acetate
tautomeric



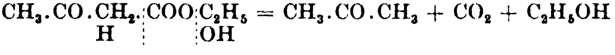
$CH_3.\overset{\frown}{CO.CHR}.COOC_2H_5$

Mono-alkyl derivative
tautomeric

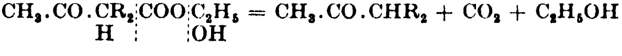
$$CH_3.CO.CRR'.COOC_2H_5$$

Di-alkyl derivative
not tautomeric

*Hydrolysis of Aceto-acetic Ester.* When heated in acid, neutral, or weakly alkaline solutions, aceto-acetic ester or its derivatives are hydrolyzed to form *ketones*.

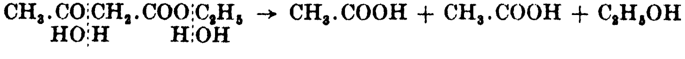


$CH_3.CO.\underset{H}{CH_2}\vdots COO\vdots\underset{OH}{C_2H_5} = CH_3.CO.CH_3 + CO_2 + C_2H_5OH$

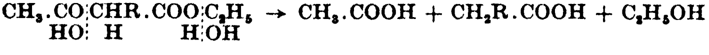


$CH_3.CO.\underset{H}{CR_2}\vdots COO\vdots\underset{OH}{C_2H_5} = CH_3.CO.CHR_2 + CO_2 + C_2H_5OH$

When heated with strong alkalis, aceto-acetic ester or its derivatives hydrolyze to form *acids*.



$CH_3.\underset{HO}{CO}\vdots\underset{H}{CH_2}.\underset{H}{COO}\vdots\underset{OH}{C_2H_5} \rightarrow CH_3.COOH + CH_3.COOH + C_2H_5OH$



$CH_3.\underset{HO}{CO}\vdots\underset{H}{CHR}.\underset{H}{COO}\vdots\underset{OH}{C_2H_5} \rightarrow CH_3.COOH + CH_2R.COOH + C_2H_5OH$

Ethyl aceto-acetate is used for the synthesis of ketones of the formulae

$$RCH_2.CO.CH_3, \quad RR'CH.CO.CH_3 \text{ (or } R_2CH.CO.CH_3\text{)},$$

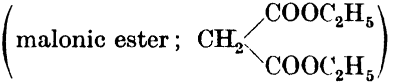
and of acids of the formulae

$$RCH_2.COOH, \quad RR'CH.COOH \text{ (or } R_2CH.COOH\text{)}$$

Ethyl malonate is often a more convenient reagent for the synthesis of acids, as on hydrolysis it yields acids only. In the case of ethyl aceto-acetate, some loss always occurs owing to the alternative hydrolysis to form a ketone.

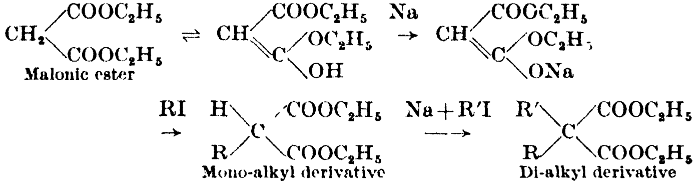
## Synthesis of Acids by means of Ethyl Malonate

Diethyl malonate

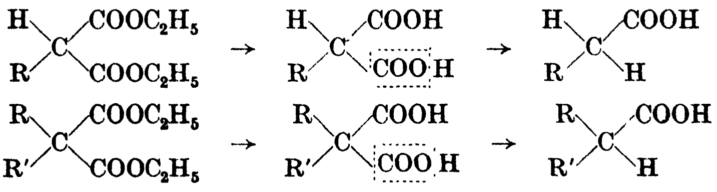


$$\left(\text{malonic ester; } CH_2\begin{matrix} \diagup COOC_2H_5 \\ \diagdown COOC_2H_5 \end{matrix}\right)$$

possesses a carbon atom, united to two hydrogen atoms, situated between two ester groups. It exists in tautomeric forms, and like ethyl aceto acetate, it forms a sodium derivative, which reacts with an alkyl halide to form a mono-alkyl derivative. The mono-alkyl derivatives are also tautomeric, and by further reaction with sodium and alkyl halides, di-alkyl derivatives of malonic ester are obtained.



When the substituted malonic esters are hydrolyzed, they form the corresponding substituted malonic acids, which on heating lose carbon dioxide, and the corresponding monobasic acid is obtained.



Malonic ester is used for synthesis of acids represented by the formulae

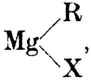
$$RCH_2.COOH \text{ and } RR'CH.COOH \text{ (or } R_2CH.COOH)$$

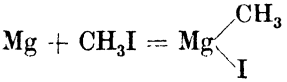
## The Organo-metallic Compounds

Many metals form compounds in which the metal atom is united directly to an alkyl group, e.g. zinc methyl $Zn(CH_3)_2$; mercury phenyl $[Hg(C_6H_5)_2]$, which is obtained by the action of sodium amalgam on bromobenzene and is used in the preparation of phenyl mercuric nitrate; lead tetra-ethyl $Pb(C_2H_5)_4$, which is used as an "anti-knock" in internal combustion engines. These derivatives are normally prepared by the direct action of the metal on the corresponding halide.

$$2CH_3I + 2Zn = Zn(CH_3)_2 + ZnI_2$$

The metal alkyls are very reactive substances.

The magnesium compounds discovered in 1901 by Grignard have been used extensively in organic synthesis. When magnesium is added to a solution of an alkyl halide in dry ether, a reaction takes place to form a compound of the formula  $\mathrm{Mg}{<}^{\mathrm{R}}_{\mathrm{X}}$, where X represents a halogen atom.

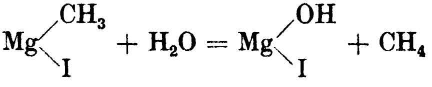


$$\mathrm{Mg} + \mathrm{CH_3I} = \mathrm{Mg}{<}^{\mathrm{CH_3}}_{\mathrm{I}}$$

These substances (which are called "*Grignard* reagents") are very reactive as shown by the following examples.

(1) *Synthesis of hydrocarbons*

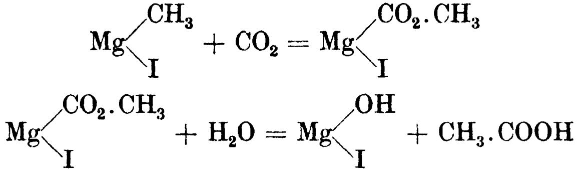
The Grignard reagents are hydrolyzed to give hydrocarbons.



$$\mathrm{Mg}{<}^{\mathrm{CH_3}}_{\mathrm{I}} + \mathrm{H_2O} = \mathrm{Mg}{<}^{\mathrm{OH}}_{\mathrm{I}} + \mathrm{CH_4}$$

(2) *Synthesis of acids*

The Grignard reagents absorb carbon dioxide, and the products on hydrolysis form acids.

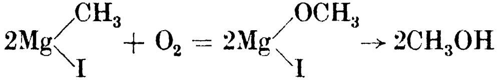


$$\mathrm{Mg}{<}^{\mathrm{CH_3}}_{\mathrm{I}} + \mathrm{CO_2} = \mathrm{Mg}{<}^{\mathrm{CO_2.CH_3}}_{\mathrm{I}}$$

$$\mathrm{Mg}{<}^{\mathrm{CO_2.CH_3}}_{\mathrm{I}} + \mathrm{H_2O} = \mathrm{Mg}{<}^{\mathrm{OH}}_{\mathrm{I}} + \mathrm{CH_3.COOH}$$

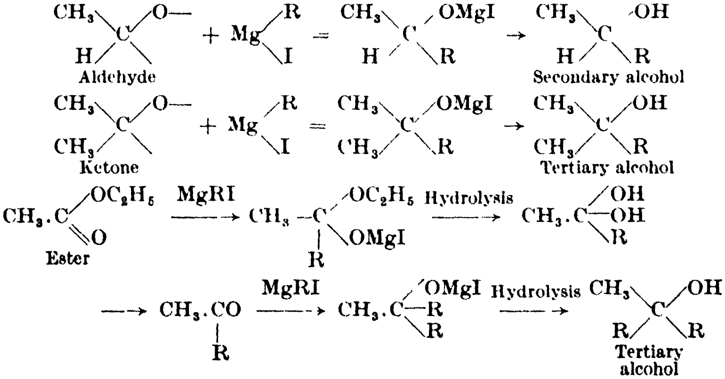
(3) *Synthesis of alcohols*

(*a*) The Grignard reagents absorb oxygen and on hydrolysis the product forms an alcohol.



$$2\mathrm{Mg}{<}^{\mathrm{CH_3}}_{\mathrm{I}} + \mathrm{O_2} = 2\mathrm{Mg}{<}^{\mathrm{OCH_3}}_{\mathrm{I}} \rightarrow 2\mathrm{CH_3OH}$$

(*b*) The commonest application of Grignard reagents depends on the following reactions. Aldehydes, ketones, and esters combine with the Grignard reagents to form substances which hydrolyze to form alcohols. Secondary alcohols are obtained from aldehydes, while ketones and esters yield tertiary alcohols. The reaction proceeds by the opening up of the carbonyl double bond and addition of the Grignard reagents. On hydrolysis the substance obtained is derived from the original aldehyde or ketone by the addition of RH to the carbonyl double bond. In the case of the ester, a further reaction takes place, and another alkyl group is introduced.



(4) Ketones and aldehydes can also be synthesized using Grignard reagents.

# CHAPTER XXX

# THE AROMATIC SERIES OF ORGANIC COMPOUNDS

THE compounds which have been discussed up to the present have all been derivatives of a series of hydrocarbons of which methane is the simplest representative. There is a large number of organic compounds which cannot be regarded as derivatives of methane but are derived from other substances. The compounds derived from the hydrocarbons benzene, naphthalene, and anthracene have been named *aromatic compounds* in contradistinction to the aliphatic compounds derived from methane.

The properties of these compounds differ in many respects from those of the corresponding aliphatic compounds. They are in general much more readily crystallized, so that experimental work with them is facilitated. The derivatives of naphthalene and anthracene resemble the corresponding derivatives of the simpler benzene series, which will be described first.

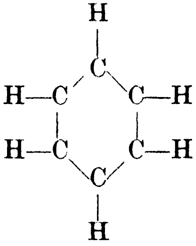
## THE BENZENE SERIES OF HYDROCARBONS

All the aromatic compounds can be derived from and converted into compounds containing *six* carbon atoms. It is not possible to break them up further into fragments containing less than six carbon atoms, without losing the characteristic aromatic properties. It follows that the nucleus of all aromatic compounds contains *six* carbon atoms. The simplest substance which possesses aromatic qualities is a hydrocarbon benzene ($C_6H_6$), and from this hydrocarbon all the other compounds are obtainable.

### The Formula of Benzene

Benzene is a compound whose molecular formula when determined by the usual methods is found to be $C_6H_6$. If regarded as a typical derivative of the aliphatic series, a substance of this formula should be highly unsaturated. (The corresponding saturated hydrocarbon of the methane series is hexane $C_6H_{14}$. Benzene contains eight fewer hydrogen atoms in the molecule and by analogy with ethylene and acetylene it should be extremely reactive by virtue of its unsaturation.) Actually benzene is not very reactive. Benzene can be made to add on six (not eight) atoms of hydrogen or chlorine, but the ordinary reactions of benzene are of a substitution nature rather than addition reactions. It is clear that a quite different type of structural formula must be adopted for the benzene compounds.

This formula (first suggested by *Kekulé*) shows that the carbon atoms (each united to one hydrogen atom) are formed into a closed regular hexagonal ring, thus—



(In this formula it will be seen that each carbon atom has only three valencies satisfied; the disposal of the fourth valencies will be discussed later, p. 478.) The evidence in favour of the hexagonal formula may be summarized as follows—

(1) The minimum number of carbon atoms in a molecule possessing aromatic properties is six.

(2) Experiments on the substitution of benzene indicate that all six of the hydrogen atoms are equivalent to one another.

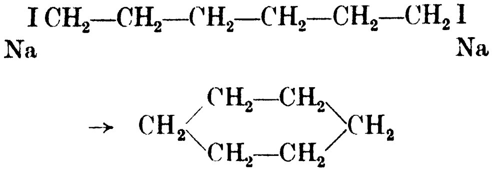
(3) The products of the addition of hydrogen or chlorine to benzene are substances of the formulae $C_6H_{12}$ and $C_6H_6Cl_6$ (a derivative of the hydrocarbon $C_6H_{12}$). These products contain six carbon atoms in a ring, as shown by typical syntheses.

When $\alpha\ \omega$ di-iodohexane

$$(ICH_2.CH_2.CH_2.CH_2.CH_2.CH_2I)$$

is heated with sodium, the hydrocarbon $C_6H_{12}$ is obtained.

The iodine atoms combine with the sodium, and the free carbon valencies are satisfied by combination involving the formation of a closed ring. The product is called cyclohexane.



$$\underset{\text{Na}}{\text{I}}\,CH_2—CH_2—CH_2—CH_2—CH_2—CH_2\,\underset{\text{Na}}{\text{I}}$$

Cyclohexane

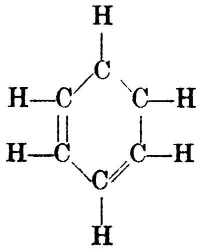
(4) Examination of crystals of benzene and its derivatives by means of X-rays indicates the presence of six carbon atoms in their molecules in the form of a flat regular hexagonal ring.

(5) The substitution products of benzene exhibit isomerism. The number of isomers obtained is in exact agreement with the number predicted from the regular hexagonal formula. No other arrangement could give such agreement.

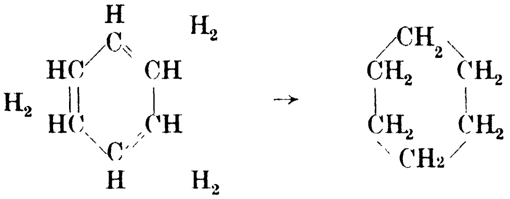
## The Problem of the Fourth Valency

The original formula as proposed by Kekulé is that most commonly adopted, and it is adequate to explain the observed behaviour of benzene and its derivatives. Other formulae arranging the fourth valency in a different manner have however been proposed.

The Kekulé formula assigns to benzene a system of three alternating single and double bonds, making each carbon atom quadrivalent, thus



This formula explains the addition reactions of benzene, addition taking place at the double bonds to form the completely saturated hydrocarbon cyclohexane.



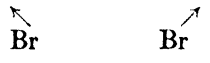
The main difficulty attached to this formula is that of explaining why these addition reactions do not take place more readily, e.g. at least as readily as for the hydrocarbon ethylene. Without entering into any detailed discussion, it will be sufficient to indicate that the behaviour of benzene in this respect is not out of keeping with the behaviour of the aliphatic compounds containing a similar arrangement of repeated alternate single and double bonds. (Double bonds thus separated by a single bond are called *conjugated* double bonds.)

The simplest body of this type is the hydrocarbon of the formula

$$CH_2{=}CH{-}CH{=}CH_2$$

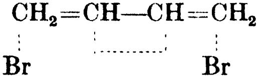
(Butadiene, the di-ethylenic derivative of butane)

In accordance with the ordinary behaviour of ethylenic compounds it would be predicted that addition of bromine would proceed at each of the double bonds. This is not what happens, for bromine normally adds at the extreme ends of the molecule and not to the central carbon atoms.



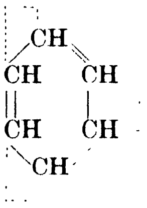
$$\underset{\underset{Br}{\nwarrow}}{CH_2}{=}CH{-}CH{=}\underset{\underset{Br}{\nearrow}}{CH_2} \rightarrow CH_2Br{-}CH{=}CH{-}CH_2Br$$

It seems that the normal attractions which the carbon atoms at either end of a double bond have for the approaching halogen atoms are not operative when two such carbon atoms are neighbours. *Thiele* pictured that these attractions (***residual valencies*** he called them) neutralized one another so that the halogen atoms are only attracted towards the end carbon atoms of the chain.

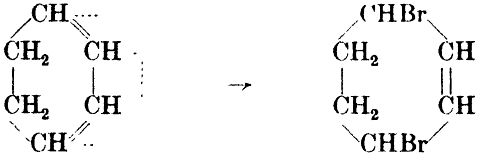


$$\underset{Br}{CH_2}{=}CH{-}CH{=}\underset{Br}{CH_2}$$

If this behaviour of the aliphatic compounds is applied to the benzene ring system, it is seen that the forces which lead to the absence of addition to the central atoms of butadiene will lead to a comparative inertness as regards addition in the case of benzene, for the neutralization of the attractions tends to be completed right round the ring.

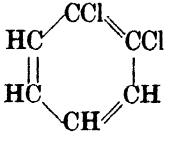


The reactivity of partially hydrogenated benzene derivatives is also in agreement. These derivatives react readily with bromine as the system of alternate double and single linkages is not complete all round the ring.

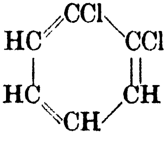


The other difficulty which is attached to the Kekulé formula for benzene is that of explaining the absence of isomeric substances depending on the relative position of the double bond, for example

(1)



(2)

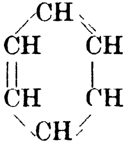


It is probable that the two isomers are so rapidly interconverted that only one derivative can be obtained. In terms of electronic theory (p. 312), this statement implies that the benzene molecule consists of "resonance hybrids."

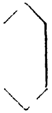
## The Isomerism of the Benzene Derivatives

When more than one of the hydrogen atoms of benzene are replaced by other atoms or radicals, isomerism becomes possible.

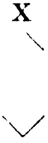
For convenience the benzene molecule is often written not as a regular hexagon but in the elongated form.



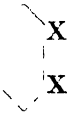
The carbon and the hydrogen atoms and the double bonds are often omitted so that the formula is written



The derivatives of benzene are written thus—



or



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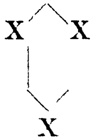
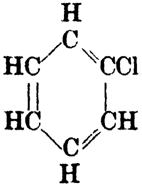
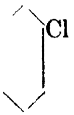


the radical X being substituted for the hydrogen atom corresponding to its position, e.g.

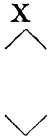


is represented by

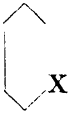


## MONO-SUBSTITUTION PRODUCTS

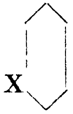
In accordance with the regular hexagonal formula for benzene, only one mono-substitution product of the formula $C_6H_5X$ is possible, and only one is obtained, e.g.



is identical with



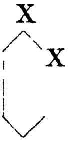
or



## DI-SUBSTITUTION PRODUCTS

In accordance with experimental observation the regular hexagonal formula indicates that there should be three isomeric derivatives of the formula $C_6H_4X_2$ or $C_6H_4XY$.

(1) Radicals adjacent. These derivatives are called the *ortho* derivatives.



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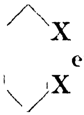
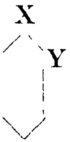


etc;



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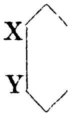
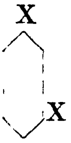


etc.

(2) Radicals separated by one carbon atom. These derivatives are called the *meta* derivatives.



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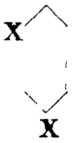
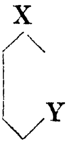


etc.;



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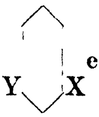
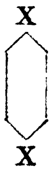


etc.

(3) Radicals opposite. These are the *para* derivatives.



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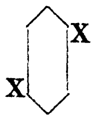
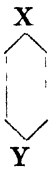


etc.;



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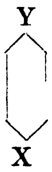
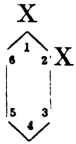


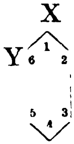
etc.

An alternative system of nomenclature is based on numbering. The carbon atoms are numbered one to six around the ring, starting at a carbon atom attached to a substituted radical.

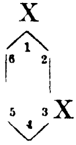
On this system—

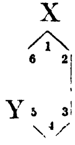
(1) The ortho derivatives are 1.2 (equivalent to 1.6) derivatives.



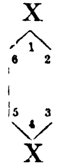


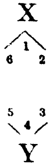
(2) The meta derivatives are the 1.3 (equivalent to 1.5) derivatives.





(3) The para derivatives are the 1.4 derivatives.

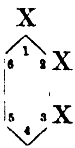




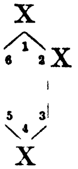
TRI-SUBSTITUTION PRODUCTS

In agreement with experiment, the regular hexagonal formula predicts three tri-derivatives of the formula $C_6H_3X_3$. When the substituent groups are not identical a greater number of isomeric tri-derivatives are possible. The three tri-derivatives of the formula $C_6H_3X_3$ are—

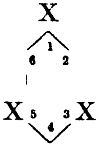
(1) Three groups adjacent, 1.2.3 derivative.



(2) Two groups adjacent, 1.2.4 derivative (equivalent to 1.3.4 or 1.3.6).



(3) Symmetrical type, 1.3.5 derivative.



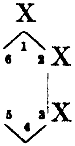
## The Orientation of the Benzene Substitution Products

The *orientation* of the benzene substitution products is the assignment of the configuration to each experimentally prepared benzene derivative.

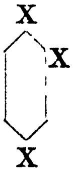
When a di-derivative ($C_6H_4X_2$) is substituted further to form a tri-derivative ($C_6H_3X_3$), the three isomeric di-derivatives give rise to different mixtures of the three isomeric tri-derivatives, thus—

(1) On further substitution, the *ortho* (1.2) derivatives yield a mixture of *two* tri-derivatives,

(*a*) on substitution in position 3 or 6 → 1.2.3 tri-derivative.

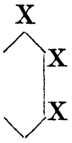


(*b*) on substitution in position 4 or 5→1.2.4. tri-derivative.

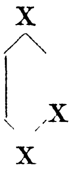


(2) *Meta* (1.3) derivatives on further substitution yield a mixture of *three* tri-derivatives,

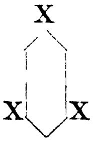
(*a*) On substitution in position 2 → 1.2.3 tri-derivative.



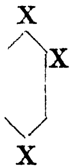
(*b*) On substitution in position 4 or 6 → 1.3.4 tri-derivative.



(*c*) On substitution in position 5 → 1.3.5. tri-derivative.



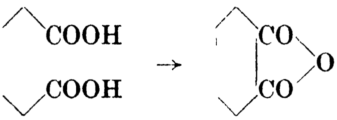
(3) *Para* (1.4) derivatives on further substitution yield *one* tri-derivative (1.2.4) only.



The configuration of the di-derivatives may be found experimentally by further substitution. The di-derivative which forms only one tri-derivative must be the para-isomer, the di-derivative which forms a mixture of two tri-derivatives will be the ortho-isomer, and the derivative which forms a mixture of three tri-derivatives must be the meta-isomer.

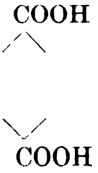
*Körner* in 1875 first developed this method of orientation. He converted the three dibromobenzenes by further bromination into the three tribromobenzenes. Other substances with different substituent groups have also been treated in this way, while the orientation of other compounds has been determined by comparison with and conversion into the corresponding bromine derivatives whose configurations were established by Körner.

Additional confirmation of the assigned configuration is obtained from the fact that of the three isomeric dicarboxylic acid derivatives of benzene [$C_6H_4(COOH)_2$], the ortho-derivative is the only one which readily forms an anhydride while the para-derivative does not form an anhydride at all.



Phthalic acid

Phthalic anhydride



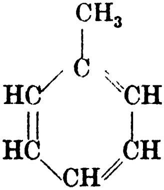
Terephthalic acid

## BENZENE AND ITS HOMOLOGUES

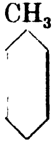
The parent substance benzene ($C_6H_6$) is the simplest member of a homologous series, all members of which have similar chemical properties. As with the homologous series of the aliphatic compounds, each member differs from the next by a $CH_2$ group, but the possibilities of isomerism are rather different from the aliphatic series.

The next member of the series after benzene is *toluene* ($C_7H_8$) and there is only one substance of this formula. Toluene is represented by the formula

$C_6H_5.CH_3$ or



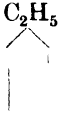
or



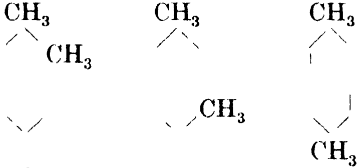
(Toluene = methylbenzene = phenylmethane)

[The benzene residue $C_6H_5$ is called the *phenyl* radical and is representable by the symbol Ph. Thus toluene could be represented by the formula Ph–Me. The general name for a radical derived from an aromatic hydrocarbon is *aryl* (to be compared with alkyl).]

The next members of the homologous series have the formula $C_8H_{10}$, and in this case there are four isomeric hydrocarbons of this formula, i.e. ethylbenzene, and the three dimethylbenzenes—ortho, meta and para. The latter three substances are called the *xylenes*.



Ethylbenzene



ortho meta para
Dimethylbenzenes or xylenes

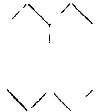
It is clear that even more isomers exist for the higher homologues.

## Preparation of the Benzene Hydrocarbons

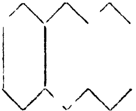
(1) On a commercial scale benzene, toluene, and the xylenes are obtained from coal-tar. The destructive distillation of coal (p. 223) yields coal-gas, a watery ammoniacal liquid, coal-tar, and coke.

Coal-tar is a black viscous liquid containing (*a*) acid substances, chiefly phenols (cf. p. 511), (*b*) basic substances (chiefly pyridine derivatives), and (*c*) neutral hydrocarbons of the aromatic series, including not only benzene and its derivatives but also derivatives of naphthalene and anthracene. These two hydrocarbons are related to benzene, as will be seen from their formulae which consist of fused benzene rings (p. 534).

Benzene



Naphthalene



Anthracene

The various constituents of coal-tar are separated by fractional distillation, the most volatile fraction and therefore the product first collected containing benzene and its homologues. Commercially the first distillate (the light oil) is collected between the ranges 80°–170°C, while succeeding fractions (middle or carbolic oil 170°–240°C, containing chiefly phenols and naphthalene, heavy oil 240°–270°C, and anthracene oil 270°–400°C, containing chiefly anthracene) are collected at higher temperatures. Finally, a residue of pitch remains in the retort.

The light oil is treated first with dilute alkali to remove phenolic impurities, then with concentrated sulphuric acid to remove basic impurities, and finally it is refractionated, thus obtaining commercial benzene (benzol), toluene (toluol), and xylene (xylol). A complete separation to prepare the pure hydrocarbons is obtained by partial freezing (cf. p. 75), and recrystallization.

Benzene hydrocarbons are present in many petroleum oils and their proportion is increased by cracking processes (p. 325). They tend to diminish "knocking" when present in motor fuel.

(2) Benzene hydrocarbons may be obtained by the action of heat on a mixture of soda lime and the sodium salt of the corresponding acid. Thus sodium benzoate and soda lime give benzene on heating. This reaction is analogous to that used for the preparation of aliphatic hydrocarbons.

$$\underset{\text{Sodium benzoate}}{C_6H_5.COONa} + NaOH = \underset{\text{Benzene}}{C_6H_6} + Na_2CO_3$$

$$\underset{\text{Sodium acetate}}{CH_3.COONa} + NaOH = \underset{\text{Methane}}{CH_4} + Na_2CO_3$$

(3) By the reaction of sodium on a mixture of an alkyl halide and a halogen derivative of a benzene hydrocarbon, a higher homologue is obtained. This reaction is analogous to the *Würtz* reaction (p. 341) in which sodium reacts with a mixture of two alkyl halides. It is usually known as *Fittig's* reaction, as Fittig first extended the reaction to the aromatic series.

$$\underset{\substack{\text{Bromobenzene}\\\text{or phenyl bromide}}}{C_6H_5Br} + CH_3Br + 2Na = 2NaBr + \underset{\text{Toluene}}{C_6H_5.CH_3}$$

$$\text{cf. } CH_3Br + C_2H_5Br + 2Na = 2NaBr + \underset{\text{Propane}}{C_3H_8}$$

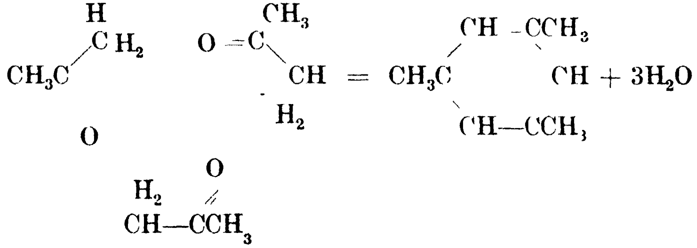
(4) The homologues of benzene may be prepared by the *Friedel* and *Craft's* reaction (p. 492), or (5) from the diazo compounds (p. 503).

(6) Some benzene is obtained when acetylene is caused to polymerize by passing through a red hot tube.

$$3C_2H_2 = C_6H_6$$

This reaction enables a complete synthesis from the constituent elements to be developed for the aromatic compounds.

(7) 1.3.5 trimethylbenzene or mesitylene is obtained by the condensation of acetone.



### Physical Properties of the Benzene Hydrocarbons

Benzene and its lower homologues are colourless, inflammable liquids, with characteristic smell and taste. They are insoluble in water, but dissolve in, and are good solvents for, most organic substances. They burn with a smoky flame.

### Chemical Properties of the Benzene Hydrocarbons

Benzene itself is rather less reactive than its homologues. It is inert to ordinary reagents (dilute acids, alkalis, oxidizing and reducing agents), but it reacts characteristically with halogens, concentrated sulphuric acid and concentrated nitric acid. The reactions with these reagents proceed more readily with the homologues, such as toluene, and in addition these hydrocarbons react with oxidizing agents.

#### Addition Reactions of Benzene

Similar addition reactions take place with the homologues of benzene.

(1) When chlorine or bromine is allowed to react with benzene in bright sunlight, three molecules of the halogen are

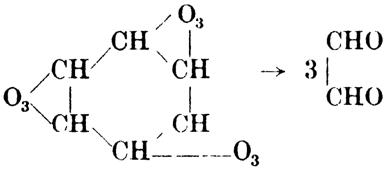
added to the benzene molecule. The product is a derivative of cyclohexane.

$$C_6H_6 + 3Cl_2 = C_6H_6Cl_6$$
$$C_6H_6 + 3Br_2 = C_6H_6Br_6$$

(2) When benzene vapour is led mixed with hydrogen over a suitable catalyst (e.g. freshly reduced nickel) addition takes place to form cyclohexane.

$$C_6H_6 + 3H_2 = C_6H_{12}$$

(3) The addition of ozone to benzene, followed by hydrolysis, leads to the formation of glyoxal by rupture of the ring.



SUBSTITUTION REACTIONS OF BENZENE

These substitution reactions are of greater practical importance than the addition reactions. They are characteristic not only of benzene and its homologues, but of aromatic compounds generally.

(1) Chlorine reacts slowly with benzene to form the substitution product chlorobenzene. This reaction takes place under different conditions from those causing addition (viz. in the dark, and in the presence of a catalyst, e.g. iodine).

$$C_6H_6 + Cl_2 = \underset{\substack{\text{Chlorobenzene}\\ \text{or phenyl chloride}}}{C_6H_5Cl} + HCl$$

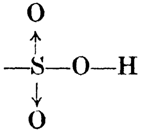
Bromine also substitutes slowly in a similar manner, but the iodine substitution product is only obtained by carrying out the reaction in the presence of nitric acid or other strong oxidizing agent.

$$2C_6H_6 + I_2 + O = 2C_6H_5I + H_2O$$

This substitution reaction is analogous to the substitution reactions of chlorine with the paraffin hydrocarbons and, as in this reaction, successive hydrogen atoms may be replaced by chlorine

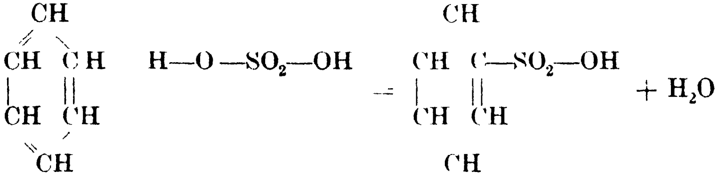
$$C_6H_5Cl + Cl_2 = C_6H_4Cl_2 + HCl$$

(2) Concentrated sulphuric acid reacts with benzene to form a substitution product with the elimination of water. The product contains the grouping



$$\overset{\displaystyle O}{\overset{\uparrow}{\underset{\underset{\displaystyle O}{\downarrow}}{—S}}}—O—H$$

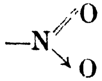
or—$SO_2OH$, and is called a sulphonic acid.



Benzene sulphonic acid

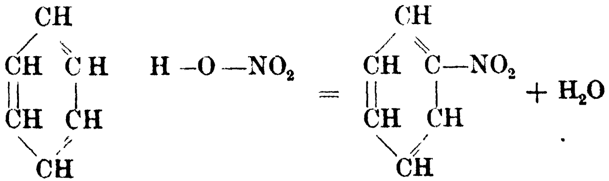
$$C_6H_6 \quad + H_2SO_4 \quad = C_6H_5SO_3H \quad + H_2O$$

(3) Concentrated nitric acid also reacts with benzene with elimination of water. The reaction is considerably accelerated by the presence of concentrated sulphuric acid, which assists in the removal of the water. The product contains the group



$$—N\begin{smallmatrix}\nearrow O\\ \searrow O\end{smallmatrix}$$

or—$NO_2$ (the nitro group).



Nitrobenzene

$$C_6H_6 \quad + HNO_3 \quad = \quad C_6H_5NO_2 \quad + H_2O$$

More concentrated acids and further length of time of reaction enable more than one hydrogen atom of benzene to be substituted, e.g. a mixture of fuming sulphuric and nitric acids forms dinitro- and at higher temperatures trinitrobenzene.

$$C_6H_6 + HNO_3 = \underset{\text{Nitrobenzene}}{C_6H_5NO_2} + H_2O$$

$$C_6H_5NO_2 + HNO_3 = \underset{\text{Dinitrobenzene}}{C_6H_4(NO_2)_2} + H_2O$$

$$C_6H_4(NO_2)_2 + HNO_3 = \underset{\text{Trinitrobenzene}}{C_6H_3(NO_2)_3} + H_2O$$

(4) The benzene hydrocarbons react with alkyl halides in the presence of anhydrous aluminium chloride as a catalyst (*Friedel and Craft's reaction*). Gaseous hydrogen halide is evolved, and a homologue of the hydrocarbon is obtained.

$$C_6H_6 + CH_3Cl = HCl + C_6H_5.CH_3$$

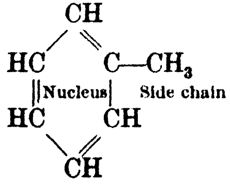
Other hydrogen atoms may be replaced by alkyl groups by further reaction. A modification in which acid chlorides are used instead of alkyl halides enables ketones to be prepared.

$$C_6H_6 + CH_3.COCl = \underset{\text{Acetophenone}}{C_6H_5.CO.CH_3} + HCl$$

Reactions 2, 3, and 4 are characteristic of the aromatic series of compounds and are not given by aliphatic compounds.

## The Special Reactions of the Homologues of Benzene

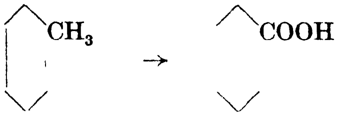
The homologues of benzene (e.g. toluene) differ from benzene itself in that in addition to the aromatic *nucleus* they also possess an aliphatic residue (which is called the *side chain*). Thus toluene $C_6H_5.CH_3$ contains the phenyl nucleus ($C_6H_5$) united to the methyl radical side chain.



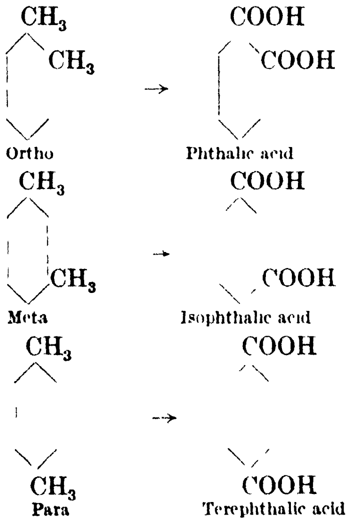
**Consequently, in addition to the reactions characteristic of the benzene aromatic nucleus, the homologues of benzene have properties due to the presence of this aliphatic side chain.**

The most important of these other properties are—

(1) *Behaviour on oxidation.* All benzene derivatives which contain an aliphatic or substituted aliphatic side chain are easily oxidized. The side chain is completely oxidized to a carboxyl group, e.g. toluene is oxidized to benzoic acid.

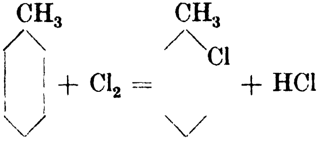


By this reaction the position of the side chain in any substance can be determined from the nature of the carboxylic acid formed, e.g. ortho-, meta- and para-xylenes form the following benzenedicarboxylic acids—

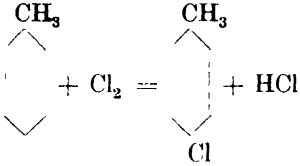


(2) *Reaction with chlorine.* Nitric and sulphuric acids react with the homologues of benzene to substitute in the aromatic nucleus. Chlorine reacts in two ways, for substitution may take place either in the aromatic nucleus or in the aliphatic side chain depending on the conditions.

(*a*) *Substitution in the nucleus.* When chlorine is passed into cold toluene, in the dark and in the presence of a catalyst (e.g. iodine), the chlorine substitutes in the nucleus to form chlorotoluenes. The derivatives have properties characteristic of the aromatic halides (p. 505).

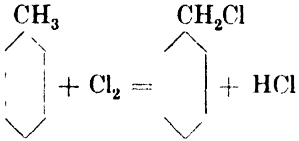


*o.* Chlorotoluene

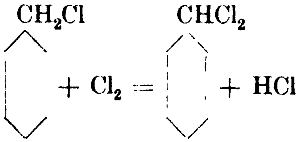


*p.* Chlorotoluene

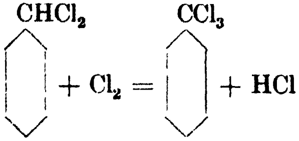
(*b*) *Substitution in the side chain.* When chlorine is passed into boiling toluene, the substitution takes place in the side chain. (Sunlight also favours side chain substitution.) The products possess properties characteristic of the aliphatic halides.



Benzylchloride



Benzalchloride

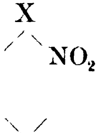


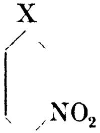
Benzotrichloride

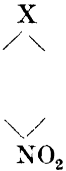
## The Nuclear Substitution of Benzene Derivatives

The ease of nuclear substitution of a benzene derivative and the products obtained depend on the nature of the compound being substituted.

When a compound $C_6H_5X$ is being substituted (for example by nitric acid), the first substitution product may be either ortho, meta, or para.


Ortho


Meta


Para

Normally not all these isomers are obtained. The nature of the radical X determines the substances produced in accordance with the two following classes.

(*a*) Some compounds on substitution form a mixture of ortho and para substitution products (X = OH, $NH_2$, $CH_3$, Cl, etc.).

(*b*) Other compounds on substitution form only the meta substitution product (X = $NO_2$, $SO_3H$, COOH, etc.).

As a general rule, the substitution of the compounds of class (*a*) proceeds fairly readily, while substitution is more difficult in the presence of one of the groups enumerated in class (*b*).

Various suggestions have been made to explain the *directional influence* of the radical X on the substitution. It seems that the groupings which are for the most part electro-positive fall into class (*a*), while electro-negative acidic groupings belong to class (*b*). It is thought that the electric charge alters the electronic arrangements of the carbon atoms forming the benzene nucleus, so that the substituting molecule is attracted to alternate carbon atoms of the ring and repelled from the intermediate atoms.

## THE AROMATIC NITRO-DERIVATIVES

The nitro-derivatives of the aromatic hydrocarbons are of practical importance, being the first stage in the conversion of the hydrocarbons into many other derivatives. They are prepared by the action of a mixture of concentrated nitric acid and sulphuric acid on the aromatic hydrocarbon.

$$C_6H_6 + HNO_3 = \underset{\text{Nitrobenzene}}{C_6H_5NO_2} + H_2O$$

## Properties of the Nitro-derivatives

The aromatic nitro-derivatives are yellow liquids or solids. They are not very reactive, the nitro group being bound strongly to the nucleus. Their importance lies mainly in their reduction products. When reduced completely they are converted into the corresponding primary amines.

$$\underset{\text{Nitrobenzene}}{C_6H_5NO_2} + 3H_2 = \underset{\text{Aniline}}{C_6H_5NH_2} + 2H_2O$$

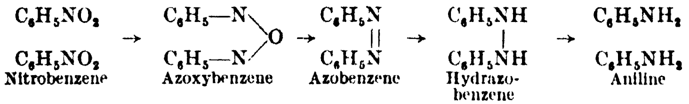
The reduction can be modified to obtain intermediate products, e.g. by adjusting the acidity or alkalinity of the solution.

The intermediate stages may be represented as follows—

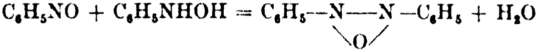
(*a*) Acid solution

$$\underset{\text{Nitrobenzene}}{C_6H_5NO_2} \rightarrow \underset{\text{Nitroso-benzene}}{C_6H_5NO} \rightarrow \underset{\text{Phenyl hydroxylamine}}{C_6H_5NHOH} \rightarrow \underset{\text{Aniline}}{C_6H_5NH_2}$$

(*b*) Alkaline solution



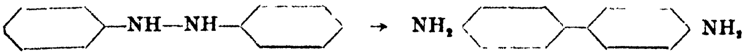
Azoxybenzene and azobenzene are probably formed by reactions between nitrosobenzene and phenyl hydroxylamine in alkaline solution.



$$C_6H_5NO + C_6H_5NHOH = C_6H_5\text{—}\underbrace{N\text{——}N}_{O}\text{—}C_6H_5 + H_2O$$

$$2C_6H_5NHOH \quad = \quad C_6H_5N{=}NC_6H_5 + 2H_2O$$

If hydrazobenzene is treated with acid it undergoes a molecular re-arrangement and produces benzidine.



Hydrazobenzene Benzidine

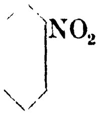
**Some highly nitrated nitro compounds are important high explosives, e.g. trinitrotoluene (T.N.T.) and trinitrophenol (picric acid).**

*Nitrobenzene* is a pale yellow liquid (b.p. 208° C.). By virtue of its characteristic smell, it is used as a cheap substitute for oil of bitter almonds in the manufacture of perfumes and scented soaps. It is prepared on a commercial scale by direct nitration of benzene with a mixture of nitric and sulphuric acids. After separating from the excess acid and washing, it is purified by steam distillation.

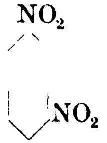
*m. Dinitrobenzene* is a solid (m.p. 90°C). It is prepared by further nitration of nitrobenzene.

*Trinitro-tertiary butyl-toluene* is manufactured for use as artificial musk.

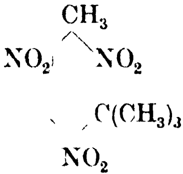
*Picric Acid* (*Symmetrical* 2.4.6. *Trinitrophenol*) is obtained by treating phenol with concentrated sulphuric acid, and adding the cold mixture to concentrated nitric acid. After warming to complete the reaction, picric acid crystallizes on cooling. It may be recrystallized from hot water. It is an intensely yellow solid (m.p. 123°C), which has been used as a dye for wool and silk, and a high explosive. Some picrates are very sensitive to shock, and care is necessary to prevent picric acid coming into contact with metals during storage.



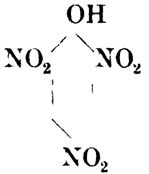
Nitrobenzene



*m.* Dinitrobenzene



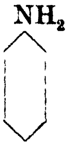
Trinitrobutyltoluene



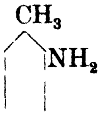
Trinitropheno

## THE AROMATIC AMINES

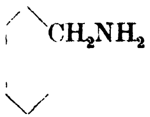
The aromatic amines (in which the amino group is united directly to the nucleus) differ to some extent from the aliphatic amines. Compounds containing an amino group in their side chain resemble the aliphatic amines (p. 431).



(*Aromatic*)
**Aminobenzene, phenylamine or aniline**



(*Aromatic*)
*o.* Aminotoluene or *o* toluidine



(*Aliphatic*)
Benzylamine

Primary, secondary, and tertiary aromatic amines and mixed aliphatic-aromatic amines may be prepared, e.g. monophenylamine (aniline) $C_6H_5NH_2$, diphenylamine $(C_6H_5)_2NH$, dimethylphenylamine (dimethylaniline) $C_6H_5N(CH_3)_2$.

The primary amines are the most important, more especially aniline ($C_6H_5NH_2$; aminobenzene, or phenylamine).

Primary aromatic amines are generally prepared by reduction of the corresponding nitro compound.

$$RNO_2 + 6H = RNH_2 + 2H_2O$$

The reduction can be carried out in various ways. In the laboratory the hydrogen evolved when tin dissolves in hydrochloric acid is used as the reducing agent. On a commercial scale the reduction is effected by iron and acid.

*Commercial manufacture of aniline from nitrobenzene.* Nitrobenzene is mixed with water and heated. Iron filings and a little hydrochloric acid or solution of ferrous chloride are added, and the reaction allowed to proceed. Ferrous chloride solution is sufficiently acid to cause the iron to react.

$$9Fe + 4H_2O + 4C_6H_5NO_2 = 4C_6H_5NH_2 + 3Fe_3O_4$$

After the reduction is complete, the mixture is poured into water and allowed to settle. The lower aniline layer is drawn off and purified by distillation.

Aniline may also be prepared by the reaction of chlorobenzene on ammonia *under pressure* in the presence of a suitable catalyst (*e.g.* cuprous chloride).

$$C_6H_5Cl + NH_3 = C_6H_5NH_2 + HCl$$

## Properties of the Primary Aromatic Amines

Aniline is a colourless liquid (b.p. 189°C), volatile in steam, with a characteristic smell. It rapidly darkens in colour on standing exposed to light. It is not very soluble in water. The toluidines (*o.*, *m.*, and *p.* amino derivatives of toluene) generally resemble aniline in their physical properties, but the *p.* isomer is a solid. The di- and higher aromatic amines are usually solids.

## General Reactions of the Primary Aromatic Amines

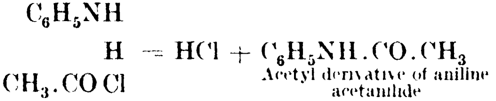
(1) The primary aromatic amines, being derivatives of ammonia, exhibit basic properties. Their basicity is however very weak and they do not give an alkaline reaction in solution. In this respect they differ from the aliphatic amines which are strong bases. The basicity of ammonia is increased by each

substitution of an alkyl group, but is weakened by the substitution of the aromatic nucleus for a hydrogen atom. Correspondingly, methylaniline ($C_6H_5NHCH_3$), and dimethylaniline ($C_6H_5N(CH_3)_2$) are stronger bases than aniline, while diphenylamine ( $(C_6H_5)_2NH$) is a very weak base, and triphenylamine ( $(C_6H_5)_3N$) has no basic properties.

The salts of the aromatic amines are soluble in water. Being easily hydrolyzed, they form acid solutions. They are easily decomposed by sodium hydroxide and other strong bases, with the formation of the free amine.

$$C_6H_5NH_2.HCl + NaOH = C_6H_5NH_2 + NaCl + H_2O$$

(2) The aromatic amines resemble the aliphatic amines in their reaction with acetic anhydride and acetyl chloride. They readily form the acetyl derivative of the amine.



$$\begin{array}{l} C_6H_5NH \\ \qquad\qquad H = HCl + \underset{\text{Acetyl derivative of aniline acetanilide}}{C_6H_5NH.CO.CH_3} \\ CH_3.CO\,Cl \end{array}$$

*Preparation of Acetanilide.* Acetanilide may be prepared by the reaction of aniline with acetic acid, acetic anhydride, or acetyl chloride. With the two latter substances the reaction proceeds rapidly in the cold; but with acetic acid in the cold aniline forms aniline acetate. On heating, this substance loses water and acetanilide is formed.

$$\underset{\text{Aniline acetate}}{C_6H_5NH_3OCO.CH_3} = H_2O + \underset{\text{Acetanilide}}{C_6H_5NH.CO.CH_3}$$

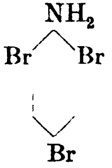
Acetanilide crystallizes from water or dilute alcohol in white plates (m.p. 112°C).

Acetanilide, like other acetyl derivatives of amines, is hydrolyzed to reform the amine and acid.

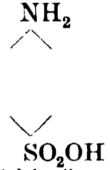
$$C_6H_5NH.CO.CH_3 + H_2O = C_6H_5NH_2 + CH_3.COOH$$

For medicinal purposes acetanilide is now largely replaced by phenacetin, which is the *p.* ethoxy derivative of acetanilide. Phenacetin ($C_2H_5O\langle\qquad\rangle NH.CO.CH_3$) is prepared by acetylation of the corresponding base *p.* phenetidine ($C_2H_5O\langle\qquad\rangle NH_2$). The official test for the absence of acetanilide in Phenacetin depends on the fact that the former substance gives a precipitate of bromacetanilide with bromine water. Phenacetin does not give a precipitate under these conditions. The assay of phenacetin in tablets containing it is based on its solubility in 95 per cent alcohol or chloroform, with which solvents it can therefore be extracted and recovered for weighing.

(3) Nuclear substitution of the aromatic amines by halogens proceeds very readily, e.g. bromine water reacts with aniline to form an immediate precipitate of 2.4.6. tribromoaniline. At ordinary temperatures, aniline reacts with sulphuric acid to form aniline sulphate, but on heating nuclear substitution takes place and *p.* aminobenzenesulphonic acid (sulphanilic acid) is formed.

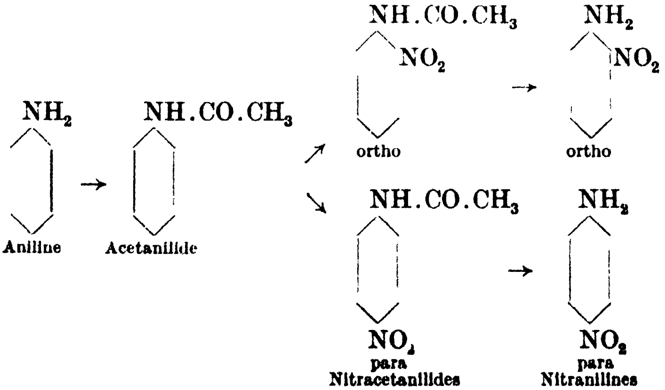


Tribromo-aniline



Sulphanilic acid

The aromatic amines are not easily nitrated directly as they are oxidized by nitric acid. But if the amino group is protected from oxidation by conversion into the acetyl derivative, nitration can be effected; e.g. for the preparation of ortho and para nitraniline, aniline is converted into acetanilide, which on nitration is converted to a mixture of *o.* and *p.* nitracetanilide. These substances on hydrolysis form the corresponding nitranilines.



(4) Aniline is readily oxidized to a number of products. The formation of a deep violet colour on the addition of bleaching powder, and a deep blue or black colour with potassium dichromate are used as tests for aniline. Diphenylamine is also readily oxidized to form a dark-coloured derivative (cf. p. 200). The oxidation of aniline with potassium dichromate and sulphuric acid is of technical importance as a source of quinone (p. 516). The reaction proceeds through several intermediate stages.

(5) The primary aromatic amines react with chloroform and caustic potash like the aliphatic amines to form isocyanides.

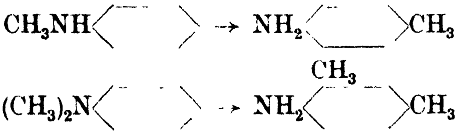
$$C_6H_5NH_2 + CHCl_3 + 3KOH = 3KCl + 3H_2O + \underset{\text{Phenyl isocyanide}}{C_6H_5NC}$$

(6) Primary aromatic amines are converted into mixed aromatic-aliphatic secondary or tertiary amines by reaction with alkyl halides.

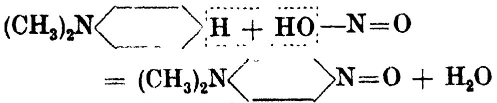
$$C_6H_5NH_2 + CH_3I = \underset{\text{Methylaniline}}{C_6H_5NHCH_3} + HI$$

$$C_6H_5NHCH_3 + CH_3I = \underset{\text{Dimethylaniline}}{C_6H_5N(CH_3)_2} + HI$$

The secondary and tertiary amines resemble in properties the aliphatic secondary and tertiary amines. In addition, on heating they undergo an intramolecular transformation, the methyl groups being transferred to the nucleus.



The *para* hydrogen atom of dimethylaniline is reactive and takes part in coupling reactions. It also reacts with nitrous acid.



Nitrosodimethylaniline

(7) The most important reaction of the primary aromatic amines is the diazo reaction. This reaction is not given by the primary aliphatic amines.

## The Diazo Reaction

Primary aliphatic amines react with nitrous acid in the cold, nitrogen being evolved instantaneously and the alcohol being formed.

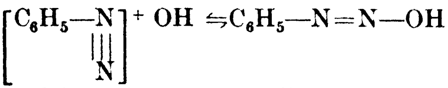
$$C_2H_5NH_2 + HNO_2 = C_2H_5OH + N_2 + H_2O$$

When nitrous acid is added to a solution of an aromatic amine in the cold, no evolution of nitrogen takes place and a yellow-coloured solution is formed which contains the *diazotized* amine. In practice, the base is dissolved in dilute acid, and while the solution is kept cool by addition of, or immersion in, ice, a solution of sodium nitrite is slowly added. Nitrous acid is formed and reacts with the amine.

$$C_2H_5NH_2 + HNO_2 = \underset{\text{Benzenediazonium hydroxide}}{C_6H_5N_2OH} + H_2O$$

The diazo compounds contain the grouping—$N_2X$ where X is usually a hydroxyl group or a halogen atom.

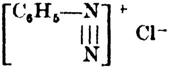
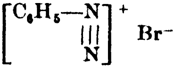
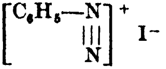
For a long time the nature of these compounds was under discussion. Some of them seemed to possess properties resembling ammonium salts which would indicate the presence of quinquevalent nitrogen, while others resembled compounds containing tervalent nitrogen. It was eventually decided that the diazonium hydroxides exist in tautomeric forms, represented by the equations



$$\underset{\text{Quinquevalent nitrogen form}}{\left[C_6H_5-\underset{\underset{N}{|||}}{N}\right]^+ \overset{-}{O}H} \leftrightharpoons \underset{\text{Tervalent nitrogen form}}{C_6H_5-N=N-OH}$$

Two sets of derivatives can therefore be obtained.

*Derivatives containing quinquevalent nitrogen.*

| | |
|---|---|
| Benzenediazonium chloride |  $\left[C_6H_5-\underset{\underset{N}{\vert\vert\vert}}{N}\right]^+ Cl^-$ |
| Benzenediazonium bromide |  $\left[C_6H_5-\underset{\underset{N}{\vert\vert\vert}}{N}\right]^+ Br^-$ |
| Benzenediazonium iodide |  $\left[C_6H_5-\underset{\underset{N}{\vert\vert\vert}}{N}\right]^+ I^-$ |

These substances are ionized in solution and in this respect resemble ammonium salts. They are therefore called diaz*onium* compounds (e.g. benzenediazonium hydroxide). In many of the reactions given below (numbers 1 to 5) the diazo compounds react in the quinquevalent nitrogen form.

*Derivative containing Tervalent Nitrogen.*

Potassium benzene diazotate $C_6H_5—N=N—OK$

In reaction 6, the diazo compounds react in the tervalent nitrogen form.

### REACTIONS OF THE DIAZO COMPOUNDS

The diazo compounds are mostly unstable, and tend to explode when isolated from solution. They are usually prepared in aqueous solution as described above, and converted directly into other substances.

The diazo group is readily replaced by other groups, nitrogen being eliminated. The new group occupies the same position in the benzene nucleus as the amino group of the original amine. Thus by means of the sequence hydrocarbon → nitro compound → amine → diazo compound, a large number of derivatives of the hydrocarbon can be obtained.

(1) When an acid solution of a diazo compound is warmed, nitrogen is evolved and the diazo group is replaced by the hydroxyl group. Thus phenol is obtained from aniline. (This replacement of a primary amino group by a hydroxyl group by the action of nitrous acid with the evolution of nitrogen may be compared with the similar replacement in the aliphatic series. In the latter case, no intermediate compound is obtained.)

$$C_6H_5NH_2 + HNO_2 = C_6H_5N_2OH + H_2O$$

$$C_6H_5N_2OH = C_6H_5OH + N_2$$

cf. $$C_2H_5NH_2 + HNO_2 = C_2H_5OH + N_2 + H_2O$$

(2) When a solution of a diazo compound is warmed after the addition of a suitable reducing agent (e.g. alcohol) the diazonium group is replaced by hydrogen, and a hydrocarbon is obtained.

$$C_6H_5N_2OH + H_2 = C_6H_6 + H_2O + N_2$$

(3) Replacement of the diazonium group by iodine is carried out by warming the solution of the diazo compound after the addition of potassium iodide.

$$C_6H_5N_2I = \underset{\text{Iodobenzene}}{C_6H_5I} + N_2$$

(4) Replacement of the diazonium group by chlorine, bromine, or cyanogen cannot be effected by the addition of the corresponding potassium salts as in the case of the iodide. But by warming in the presence of cuprous chloride, cuprous bromide or cuprous cyanide the corresponding replacement takes place. This reaction, which is known as *Sandmeyer's* reaction, is an important stage in the conversion of aromatic hydrocarbons into their halogen, cyanogen, and (by hydrolysis) carboxyl derivatives.

$$C_6H_5N_2Cl = \underset{\substack{\text{Phenyl chloride} \\ \text{or chlorobenzene}}}{C_6H_5Cl} + N_2$$

$$C_6H_5N_2Br = \underset{\text{Bromobenzene}}{C_6H_5Br} + N_2$$

$$C_6H_5N_2CN = \underset{\substack{\text{Phenyl cyanide,} \\ \text{cyanobenzene} \\ \text{or benzonitrile}}}{C_6H_5CN} + N_2$$

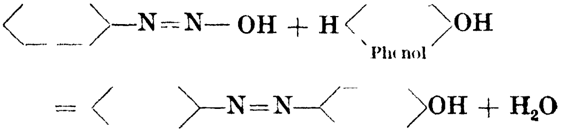
$$C_6H_5CN \xrightarrow{\text{hydrolysis}} \underset{\text{Benzoic acid}}{C_6H_6COOH}$$

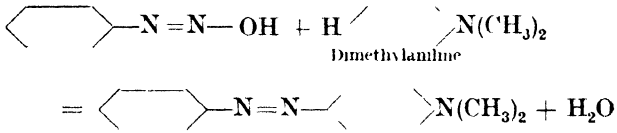
(5) Diazo compounds take part in two important reactions which proceed without elimination of nitrogen. The diazo compounds may be reduced with stannous chloride or sulphur dioxide to form derivatives of hydrazine. Phenylhydrazine (which is an important reagent for the detection of aldehydes, ketones, and sugars) is obtained from aniline by diazotization and reduction.

$$C_6H_5\text{—}N{=}N\text{—}OH + 2H_2 = \underset{\text{Phenylhydrazine}}{C_6H_5NH\text{—}NH_2} + H_2O$$

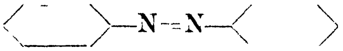
(6) The diazo compounds are of technical importance by reason of their *coupling reactions.* These reactions take

place between the diazo compounds and aromatic amines or phenols.





The resultant compounds (the azo dyes) contain a skeleton consisting of two benzene nuclei united by an *azo* (—N=N—) group.



They are stable non-reactive substances, whose colour can be varied by the presence of different groups substituted in the two benzene nuclei. The presence of the hydroxyl or amino group, from the original phenol or amine, confers acidic or basic properties which help to fix the dye in the fibres of the fabric.

## THE AROMATIC HALOGEN DERIVATIVES

Nuclear substituted halogen derivatives of benzene and its homologues differ in many ways from the aliphatic halides. The compounds obtained by introducing halogens into the side chain of a benzene homologue resemble the alkyl halides in their properties.

### Preparation of Aromatic Halides

(1) Nuclear substituted benzene derivatives may be obtained by direct substitution (cf. p. 490).

(2) They are conveniently prepared from the diazo compounds (p. 504).

## Properties of the Aromatic Halides

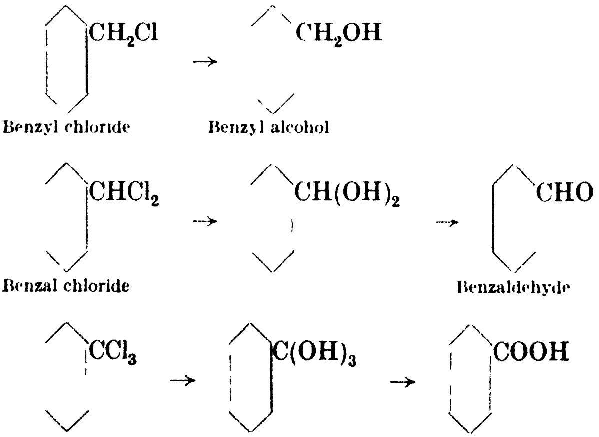
The nuclear substituted halogen derivatives are pleasant smelling liquids, insoluble in water.

In the *nuclear* substituted halogen compounds, the halogen atom is bound strongly to the nucleus, and is comparatively unreactive. For example, the aryl halides differ from the alkyl halides in that they do not react readily with caustic potash and ammonia.

The reactions with sodium (p. 488) and magnesium (p. 474) are common to both classes of halides.

The *side chain* substituted compounds react with caustic potash and ammonia like alkyl halides, the halogen atom being replaced by a hydroxyl or an amino group.

Benzyl chloride, benzal chloride, and benzo-trichloride are obtained by the side chain chlorination of toluene. These compounds react with caustic potash to form benzyl alcohol, benzaldehyde, and benzoic acid respectively.



Benzyl chloride Benzyl alcohol

Benzal chloride Benzaldehyde

Benzotrichloride Benzoic acid

**The side chain substituted halides possess an irritating and unpleasant smell.**

## THE AROMATIC SULPHONIC ACIDS

Aromatic hydrocarbons may be converted into other derivatives not only by first preparing the nitro derivative but also by forming the sulphonic acid derivative.

When the hydrocarbon is treated with concentrated or fuming sulphuric acid, substitution of one or more hydrogen atoms takes place and the sulphonic acid group is introduced. The sulphonic acids are soluble, strong, monobasic acids, which are easily converted into their salts.

$$\underset{\text{Benzene}}{C_6H_5H} + \underset{\text{Sulphuric acid}}{HO{-}SO_2OH} = \underset{\text{Benzenesulphonic acid}}{C_6H_5SO_2OH} + H_2O$$

$$C_6H_5.SO_2OH + KOH = \underset{\text{Potassium benzenesulphonate}}{C_6H_5.SO_2OK} + H_2O$$

When the alkali salts of sulphonic acids are *fused* with potassium hydroxide or potassium cyanide, reactions take place by which the sulphonic acid group is replaced by a hydroxyl or cyanide radical. Thus through the formation of a sulphonic acid, an aromatic hydrocarbon may be converted to its hydroxyl, cyanide, or carboxyl derivative.

$$C_6H_5.SO_3K + KOH = KHSO_3 + C_6H_5OK$$

$$C_6H_5.SO_3K + KCN = K_2SO_3 + C_6H_5CN$$

The hydroxyl group of the aromatic sulphonic acids reacts with phosphorus pentachloride and ammonia similarly to the hydroxyl groups of the carboxylic acids. The products (sulphonic chlorides and sulphonamides) resemble the corresponding acid chlorides and acid amides.

$$2C_6H_5.SO_2OH + PCl_5 = POCl_3 + H_2O + \underset{\text{Benzene sulphonic chloride}}{2C_6H_5.SO_2Cl}$$

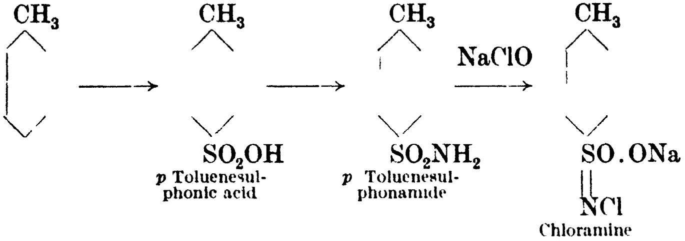
cf. $$2CH_3.COOH + PCl_5 = POCl_3 + H_2O + 2CH_3.COCl$$

$$C_6H_5.SO_2OH + NH_3 = H_2O + \underset{\text{Benzenesulphonamide}}{C_6H_5.SO_2NH_2}$$

cf. $$CH_3.COOH + NH_3 = H_2O + CH_3.CONH_2$$

## Derivatives of the Sulphonamides

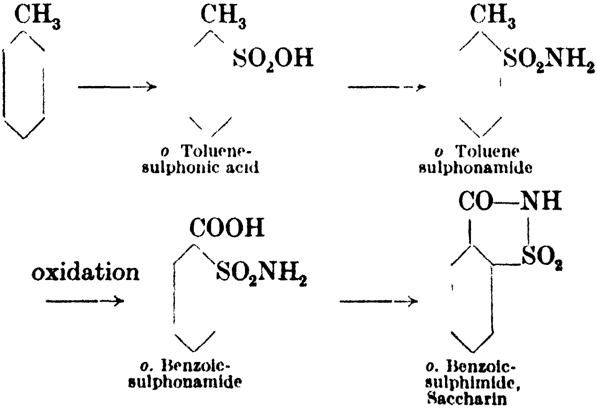
*Chloramine* is a derivative of *p.* toluenesulphonamide, and is obtained from it by reaction with sodium hypochlorite.



Chloramine (which crystallizes with three molecules of water of crystallization) is assayed officially on its oxidizing properties. It liberates iodine from an acidified solution of potassium iodide.

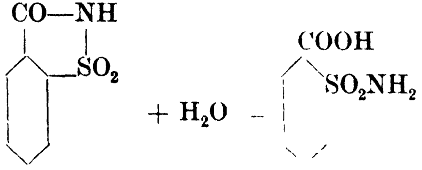
$$\begin{aligned} &CH_3.C_6H_4.SO_2.N\ NaCl + 2HI \\ &\quad = CH_3.C_6H_4.SO_2NH_2 + NaCl + I_2 \end{aligned}$$

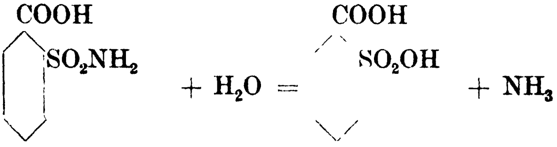
*Saccharin* is an internal anhydride of *o.* benzoicsulphonamide. It is prepared in accordance with the following scheme.



**Soluble Saccharin is the sodium salt of this compound, the imido group (NH) being acidic (cf. p. 443). Saccharin is**

officially assayed by a hydrolytic reaction which converts it first into *o.* benzoicsulphonamide and then into ammonia. The final hydrolysis is carried out in acid solution to fix the ammonia, which is then determined by adding alkali and distilling into standard acid.





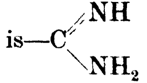
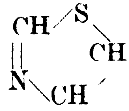
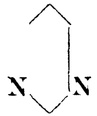
*Sulphanilamide* ($NH_2.C_6H_4.SO_2.NH_2$) is the sulphonamide of sulphanilic acid (p. 500). The manufacturing method of preparation involves the chlorosulphonation of acetanilide, using chlorosulphonic acid, and the preparation of acetylsulphanilamide, which is then hydrolyzed.

$$CH_3.CO.NH.C_6H_5 \xrightarrow{ClSO_2OH} CH_3.CO.NH.C_6H_4.SO_2Cl \longrightarrow$$
$$CH_3.CO.NH.C_6H_4.SO_2.NH_2 \longrightarrow NH_2.C_6H_4.SO_2.NH_2$$

In addition to the sulphonamide grouping, sulphanilamide contains a free amino group and consequently reacts with nitrous acid. The resulting solution couples with $\beta$ naphthol to give an orange coloured azo dyestuff. The official assay process is based on the reaction with nitrous acid, the acidified sulphanilamide solution being titrated with sodium nitrite until excess nitrous acid is just formed, as shown by its libration of iodine from potassium iodide.

$$HNO_2 + NH_2.C_6H_4.SO_2.NH_2 + HCl$$
$$= Cl.N_2.C_6H_4.SO_2.NH_2 + 2H_2O$$

*The Derivatives of Sulphanilamide* contain one hydrogen atom of the sulphonamide group substituted, i.e.

$NH_2.C_6H_4.SO_2.NHR$. R is acetyl($-COCH_3$) in sulphacetamide, and is  $-C{\scriptsize\begin{matrix}\nearrow NH\\ \searrow NH_2\end{matrix}}$ in sulphaguanidine [guanidine is $NH{=}C(NH_2)_2$]; while in sulphathiazole and sulphadiazine the radical R is respectively the thiazole  and diazine  ring systems. In these derivatives the hydrogen of the $-SO_2.NHR$ group is acidic and sodium salts are formed by interaction with sodium hydroxide. The derivatives can be prepared either from sulphanilamide itself (e.g. by acetylation or reaction with dicyandiamide), or from the corresponding amine compound by reaction with the sulphonylchloride of sulphanilic acid.

$$2NH_2.C_6H_4.SO_2NH_2 + (CH_3.CO)_2O = \underset{\text{Sulphacetamide}}{2NH_2.C_6H_4.SO_2.NH.CO.CH_3} + H_2O$$

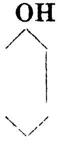
$$NH_2.C_6H_4.SO_2.NH_2 + NHCN.C(NH_2){=}NH + 2H_2O \longrightarrow \underset{\text{Sulphaguanidine}}{NH_2.C_6H_4.SO_2.NH.C(NH_2){=}NH} + CO_2 + 2NH_3$$

$$NH_2.C_6H_4.SO_2Cl + NH_2R = NH_2.C_6H_4.SO_2.NHR + HC$$

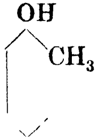
Since the sulphanilamide derivatives contain a free amino group they can be assayed by titration with nitrous acid. Succinylthiazole is exceptional in that its amino group is substituted by the monosuccinyl radical.

## THE AROMATIC HYDROXYL COMPOUNDS

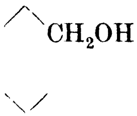
The hydroxyl derivatives of the aromatic hydrocarbons in which the hydroxyl group has been substituted in the nucleus are the *phenols*, whose properties are different from those of the aliphatic alcohols. Derivatives containing the hydroxyl group in the side chain (the aromatic alcohols) resemble in properties the aliphatic alcohols. The lowest member of the series of phenols is itself called phenol.



Phenol



Cresol (phenolic)



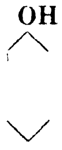
Benzyl alcohol

## General Methods of Preparation of Phenols

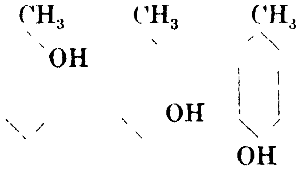
(1) Phenol is obtained from the tars produced by the destructive distillation of coal and wood. Coal-tar is the most important source of phenol ($C_6H_5OH$) and its simpler homologues.

*The Separation of Phenols from Coal-tar.* When coal-tar is distilled, the phenol is contained in the middle or carbolic oil. On cooling, the naphthalene in this oil crystallizes, while the phenols remain in the liquid fraction. This is treated with caustic soda solution in which the phenol dissolves. The non-acidic impurities are separated. The phenol solution is then acidified (often by passing in carbon dioxide), when the phenol separates. It is purified further by distillation.

*The Cresols* (the next members of the homologous series of phenols) are also obtained from coal-tar. The separation of the isomers is not easy, and is not carried out for ordinary purposes.



Phenol



ortho meta para
Cresols

(2) Phenols may be prepared by fusing the sodium salt of a sulphonic acid with sodium hydroxide. This method of preparation can be applied on a large scale.

$$C_6H_5SO_2ONa + NaOH = NaHSO_3 + C_6H_5ONa$$

(3) Phenols may be prepared from the amines by the diazo reaction (p. 502).

(4) Phenol can be obtained by heating the corresponding chlorine derivative with alkali *at high temperature under pressure.*

$$C_6H_5Cl + KOH = KCl + C_6H_5OH$$

## General Reactions of the Phenols

(1) The most important difference between the hydroxy-compounds of the aromatic and aliphatic series lies in the acidity of the former. Phenol is a weak acid. It is not very soluble in water but dissolves readily as its salt on the addition of alkali. (The alcohols do not exhibit acidic properties.)

$$C_6H_5OH + NaOH = \underset{\text{Sodium phenate or phenoxide}}{C_6H_5ONa} + H_2O$$

Phenol is a very weak acid, and its salts are easily decomposed by the addition of stronger acids. The passage of carbon dioxide into a solution of sodium phenate is sufficient to cause the phenol to be displaced from solution.

Although phenol itself is such a weak acid, the introduction of other groups into the benzene nucleus may increase the acidity and trinitrophenol forms well-defined picrate salts.

(2) Phenols resemble alcohols in their capacity for forming ethers and esters.

When an acid chloride or acid anhydride reacts on a phenol the corresponding ester is obtained.

$$\underset{\text{Phenol}}{C_6H_5OH} + \underset{\text{Benzoyl chloride}}{C_6H_5.COCl} = HCl + \underset{\text{Phenyl benzoate}}{C_6H_5.COOC_6H_5}$$

(3) Ethers are prepared from phenols by reacting with an alkyl halide on their sodium salts. In this way a mixed aliphatic aromatic ether is obtained. Purely aromatic ethers can also be prepared (*e.g.* $C_6H_5—O—C_6H_5$ diphenyl ether).

$$C_6H_5ONa + CH_3I = NaI + \underset{\substack{\text{Phenyl methyl ether}\\ \text{(anisole)}}}{C_6H_5OCH_3}$$

$$C_6H_5ONa + C_2H_5I = NaI + \underset{\substack{\text{Phenyl ethyl ether}\\ \text{(phenetole)}}}{C_6H_5OC_2H_5}$$

(4) Another point of resemblance between the phenols and the alcohols is in the reaction with phosphorus pentachloride, whereby the hydroxyl group is replaced by chlorine.

$$C_6H_5OH + PCl_5 = POCl_3 + HCl + C_6H_5Cl$$

(5) The aromatic nucleus present in the phenol molecule is readily substituted by the ordinary aromatic substituting reagents; e.g. *dilute* nitric acid converts phenol into a mixture of *o.* and *p.* mononitrophenol, while a mixture of *concentrated* sulphuric and nitric acids forms the trinitro derivative. Bromine water added to a dilute solution of phenol produces an immediate precipitate of tribromophenol.

$$C_6H_5OH + 3Br_2 = C_6H_2Br_3OH + 3HBr$$

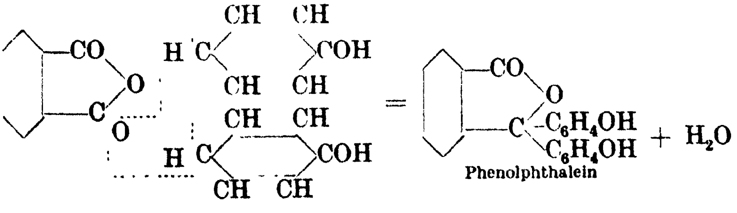
Phenoldisulphonic acid, obtained by the action of concentrated sulphuric acid on phenol, is itself readily nitrated, forming a strongly coloured nitro-derivative. This reaction is applicable to the detection of small quantities of nitrates, e.g. in water where the presence of nitrites does not interfere, and it is also used in the official assay of Tablets of Glyceryl Trinitrate (p. 396).

(6) Phenols can be reduced to the corresponding hydrocarbon by heating with zinc dust.

$$C_6H_5OH + Zn = ZnO + C_6H_6$$

(7) Phenols combine with diazotized aromatic amines to form the azo dyes.

(8) Phenols condense with phthalic anhydride (p. 525) in the presence of dehydrating agents to form substances called *phthaleins*. An oxygen atom of the phthalic anhydride combines with one *nuclear* hydrogen atom from each of two phenol molecules. The resultant compound is a derivative of phthalic anhydride with two phenol residues replacing an oxygen atom.



The simplest member of this class of substance (many of which are of industrial importance as dyes) is phenolphthalein.

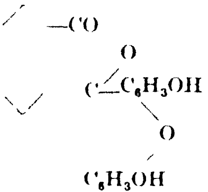
*Phenolphthalein* is obtained by heating phenol and phthalic anhydride to about 120°C. with concentrated sulphuric acid (which acts as a dehydrating agent). It is a white crystalline substance almost insoluble in water, but soluble in alkalis forming a red solution. (The colour change is due to an intramolecular rearrangement which accompanies ionization, p. 49.)

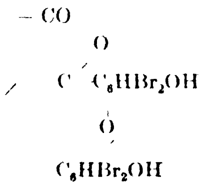
When other phenolic substances are condensed with phthalic anhydride, other phthaleins are obtained, e.g. when resorcinol is used, resorcinolphthalein or fluorescein is obtained.

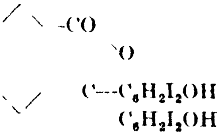
*Fluorescein* is characterized by the brilliant greenish yellow fluorescence of its solutions. Many of its derivatives are also fluorescent. Fluorescein Sodium is the di-sodium salt of fluorescein, salt formation involving a molecular rearrangement.

When fluorescein is treated with bromine, the resorcinol residues become substituted and tetrabromofluorescein is obtained, the sodium salt of which is *eosin*.

Similarly, iodine reacts with phenolphthalein to form tetraiodophenolphthalein, whose sodium salt is *Iodophthalein*.


Fluorescein


Eosin


Iodophthalein

(9) Many phenols react with sodium nitrite in presence of concentrated sulphuric acid to form *nitrosophenols*, which give characteristic colour reactions (*Liebermann's test*).

$$C_6H_5OH + HNO_2 = \underset{\text{Nitrosophenol}}{HOC_6H_4NO} + H_2O$$

*Phenol*, carbolic acid ($C_6H_5OH$) (the simplest member of the homologous series), occurs as colourless crystals, which become pink on keeping. It possesses a characteristic odour.

The precipitation of the tribromo- derivative from aqueous solution by reaction with bromine water, is used as a test for phenol, and as the basis of its official assay.

$$C_6H_5OH + 3Br_2 = \underset{\text{Tribromophenol}}{C_6H_2Br_3OH} + 3HBr$$

For the assay a measured quantity of Phenol is shaken for half an hour in a well-stoppered bottle with a standard solution of bromine (prepared from a solution of potassium bromide and bromate from which bromine is liberated on acidifying, cf. p. 163). After the bromination of the phenol is complete, the excess bromine is determined by addition of potassium iodide and titration of the liberated iodine with sodium thiosulphate.

$$Br_2 + 2KI = 2KBr + I_2$$

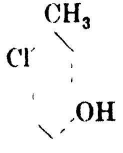
*Cresols.* The three isomeric hydroxytoluenes are not usually separated from one another, but marketed as a mixture. Cresol B.P. is a light-coloured liquid with a characteristic smell. It is soluble in 50 parts of water. The official purity tests for the presence of hydrocarbons (naphthalene, etc.) and bases (pyridine, etc.) depend on the fixation of the phenolic cresols by alkali, and separation of the hydrocarbons and the bases by distillation. The volume of the oily distillate is measured, the basic constituents are determined by titration with acid, and the hydrocarbons found by difference.

The cresol present in *Solution of Cresol with Soap* is assayed after it has been separated from the saponaceous matter by steam distillation.

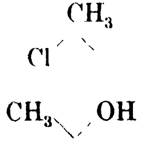
*Chlorocresol* (*p*.chloro-*m*.cresol) is obtained by direct chlorination of *m*. cresol.

*Chloroxylenol* is prepared from *m*. xylenol which occurs in coal tar and is chlorinated using sulphuryl chloride as the chlorinating agent.

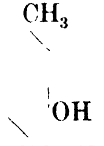
*Thymol* is a homologue of phenol which occurs in oil of thyme, and it may also be obtained from certain terpenes (p. 553) to which it is structurally related.



Chlorocresol



Chloroxylenol



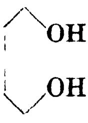
Thymol

## The Dihydric and Trihydric Phenols

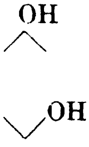
In addition to the characteristic phenolic properties, many of the di- and tri-hydric phenols possess reducing properties in alkaline solution. Some are used as photographic developers.

### DIHYDROXYBENZENES

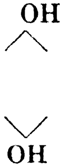
The three isomeric dihydroxybenzenes are known as catechol, resorcinol, and hydroquinone (quinol).



ortho
Catechol



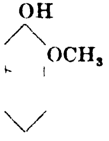
meta
Resorcinol



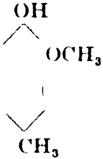
para
Hydroquinone or quinol

*Catechol* is obtained from various plant sources and from wood-tar. The corresponding mono-ether *guaiacol* is an important constituent of wood-tar from which it is obtainable by fractional distillation. It can also be prepared synthetically.

*Creosol*, another constituent of wood-tar, is a homologue of guaiacol.



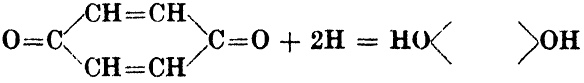
Guaiacol



Creosol

*Resorcinol* is prepared on the technical scale synthetically. Benzene when sulphonated with fuming sulphuric acid forms the meta-disulphonic acid, from which by fusion with alkali meta-dihydroxybenzene is obtained.

*Hydroquinone* or *Quinol* is prepared by reduction of quinone. It is a valuable photographic developer.



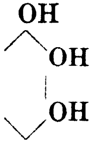
$$O{=}C\begin{matrix}CH{=}CH\\CH{=}CH\end{matrix}C{=}O + 2H = HO\langle\quad\rangle OH$$

Quinone

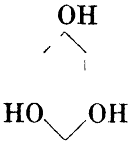
[*Quinone* (or *Benzoquinone*) is an unsaturated ketone, and undergoes the corresponding reactions. It does not possess aromatic properties].

TRIHYDROXYBENZENES

The three possible isomerides are

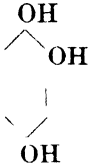


Pyrogallol
1.2 3.



Phloroglucinol
1 3 5.

1.2.4.



1 2 4 Trihydroxy-benzene

*Pyrogallol* is prepared by the action of heat on gallic acid. It is easily oxidized in alkaline solution, and is used as a photographic developer and to absorb oxygen in gas analysis.

## THE AROMATIC ALCOHOLS

The aromatic alcohols contain a hydroxyl group in the side chain. They are prepared by reactions comparable with those of the aliphatic alcohols, and in their general properties resemble those of the aliphatic series.

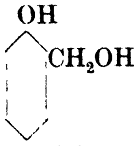
*Benzyl Alcohol* ($C_6H_5.CH_2OH$) is prepared by hydrolysis of the corresponding halogen derivative which is obtained from toluene by side chain substitution. It is oxidized to the corresponding aldehyde and acid, and is assayed by its esterification reaction with acetic anhydride.

$$C_6H_5.CH_3 \rightarrow C_6H_5.CH_2Cl \rightarrow C_6H_5.CH_2OH$$

$$\underset{\text{Benzyl alcohol}}{C_6H_5.CH_2OH} \rightarrow \underset{\text{Benzaldehyde}}{C_6H_5.CHO} \rightarrow \underset{\text{Benzoic acid}}{C_6H_5.COOH}$$

$$\underset{\text{Benzyl alcohol}}{2C_6H_5.CH_2OH} + \underset{\text{Acetic anhydride}}{(CH_3.CO)_2O} \rightarrow \underset{\text{Benzyl acetate}}{2CH_3.COO.CH_2.C_6H_5} + H_2O$$

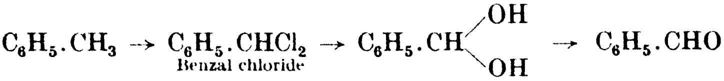
*Salicyl Alcohol* (which is obtained by hydrolysis of the glucoside salicin) is a phenolic alcohol which is oxidized to salicylic acid.



Salicyl alcohol

## THE AROMATIC ALDEHYDES

The aromatic aldehydes resemble those of the aliphatic series, and are prepared in a similar way. For example, benzaldehyde can be prepared by oxidation of benzyl alcohol, or from benzyl chloride or bromide by simultaneous hydrolysis and oxidation by heating with a solution of lead, copper, or sodium nitrate. It can also be prepared by hydrolysis of benzal chloride.



$$C_6H_5.CH_3 \rightarrow \underset{\text{Benzal chloride}}{C_6H_5.CHCl_2} \rightarrow C_6H_5.CH\begin{matrix}OH\\OH\end{matrix} \rightarrow C_6H_5.CHO$$

The last two reactions are applied in the preparation of benzaldehyde from toluene on a commercial scale.

Benzaldehyde is also obtained from the glucoside amygdalin, which occurs in bitter almonds. On hydrolysis amygdalin forms glucose, hydrogen cyanide and benzaldehyde.

$$C_{20}H_{27}NO_{11} + 2H_2O = C_6H_5.CHO + 2C_6H_{12}O_6 + HCN$$

Benzaldehyde is a liquid with an almond-like smell (oil of bitter almonds).

### Properties of the Aromatic Aldehydes

The aromatic aldehydes like the aliphatic aldehydes are easily oxidized to the corresponding acids (benzaldehyde, unless very pure, absorbs oxygen readily from the air; but although benzaldehyde reduces ammoniacal silver nitrate, it does not reduce Fehling's solution). The aromatic aldehydes form condensation products with hydroxylamine and phenylhydrazine, and form addition products with sodium bisulphite and hydrogen cyanide. Nuclear aromatic aldehydes (e.g. benzaldehyde) are more reactive than the aliphatic aldehydes, and take part in the following additional reactions.

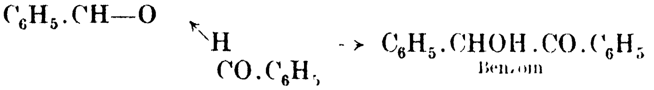
(1) With ammonia, a simple addition product is not formed, but a more complex reaction takes place.

$$3C_6H_5.CHO + 2NH_3 = \underset{\text{Hydrobenzamide}}{(C_6H_5.CH)_3N_2} + 3H_2O$$

(2) In presence of alkalis, simultaneous oxidation and reduction take place, and a mixture of the corresponding acid and alcohol is formed (*Cannizzaro reaction*).

$$2C_6H_5.CHO + NaOH = C_6H_5.COONa + C_6H_5.CH_2OH$$

(3) In the presence of potassium cyanide, benzaldehyde undergoes the *benzoin condensation.* A ketonic alcohol is obtained by the union of two molecules of the aldehyde.



$$C_6H_5.CH{-}O \quad \overset{\nwarrow}{H} \quad CO.C_6H_5 \rightarrow \underset{\text{Benzoin}}{C_6H_5.CHOH.CO.C_6H_5}$$

(4) The oxygen of the carbonyl group of the aromatic aldehydes is capable of removing hydrogen (as water) from the molecules of many other substances, e.g. benzaldehyde condenses with aliphatic aldehydes to form unsaturated aldehydes.

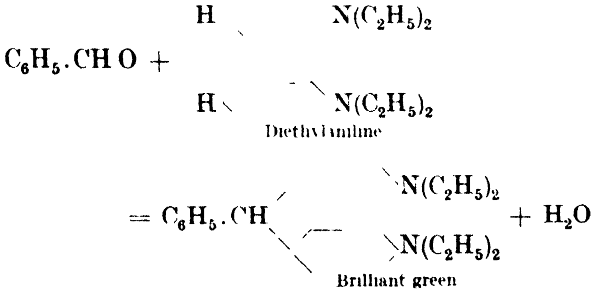
$$C_6H_5.CHO + CH_3.CHO = \underset{\text{Cinnamic aldehyde}}{C_6H_5.CH{=}CH.CHO} + H_2O$$

When benzaldehyde reacts with a mixture of a sodium salt of a fatty acid and the acid anhydride, an unsaturated acid is obtained. A similar reaction is given by some aliphatic aldehydes (*Perkin reaction*).

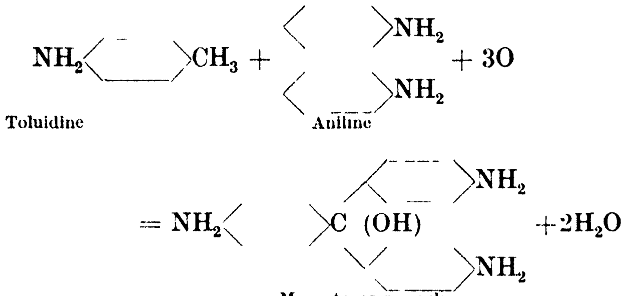
$$C_6H_5.CH\,O + H_2CH.COONa$$

$$= \underset{\text{Sodium cinnamate}}{C_6H_5.CH{=}CH.COONa} + H_2O$$

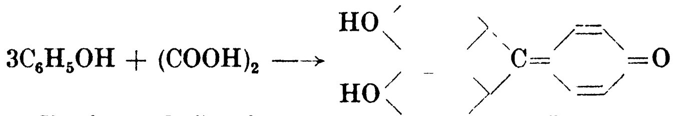
The condensation products obtained from the alkyl anilines or phenols are important dyes (triphenylmethane derivatives).



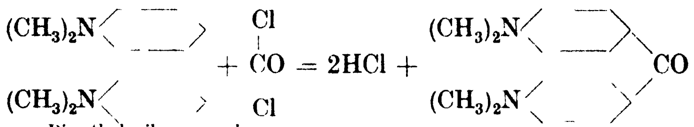
Similar triphenylmethane dyes are obtained by other reactions, e.g. magenta from aniline and *p.* toluidine in presence of an oxidizing agent (nitrobenzene); aurine (corallin) from phenol, oxalic acid and sulphuric acid, and crystal violet from dimethylaniline and the product of the action of phosgene on dimethylaniline (tetramethyl-diaminobenzophenone). All these dyestuffs form salts accompanied by readjustment of the double bonds within the ring systems. (Strictly speaking, the names Brilliant Green, Magenta, Corallin and Crystal Violet refer to the salts.)



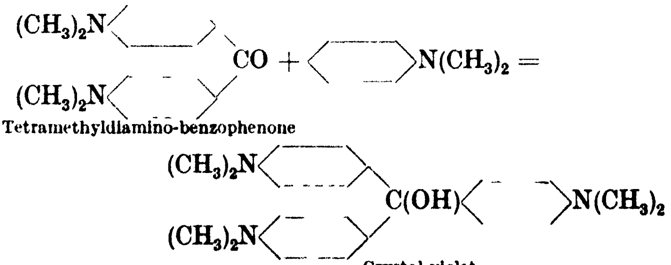
Magenta or rosaniline



Phenol Oxalic acid Aurine or corallin



Dimethylaniline phosgene



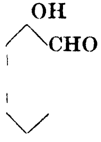
Crystal violet

### HYDROXY ALDEHYDES

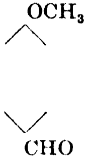
The most important hydroxy aldehyde is *salicylaldehyde.*

*Anisaldehyde* is an ether of the corresponding *p.* hydroxy benzaldehyde. It occurs in some essential oils.

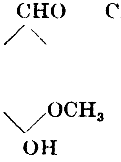
*Vanillin* is an ether of a dihydroxy aldehyde. It is prepared from *eugenol* which is the chief constituent of oil of cloves.



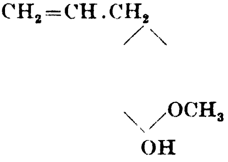
Salicylaldehyde



Anisaldehyde



Vanillin



Eugenol

### UNSATURATED ALDEHYDES

Cinnamic aldehyde ($C_6H_5.CH{=}CH.CHO$) is the chief constituent of oil of cinnamon.

## THE AROMATIC ACIDS

The aromatic acids occur naturally in the free and combined states. They may be prepared from their naturally occurring derivatives, and synthetically by the following general methods.

(1) By oxidation of aromatic compounds which contain an aliphatic side chain. On oxidation the side chain is converted into a carboxyl group.

$$\underset{\text{Toluene}}{C_6H_5.CH_3} \rightarrow \underset{\text{Benzoic acid}}{C_6H_5.COOH}$$

(2) By oxidation of the corresponding alcohols and aldehydes.

$$C_6H_5.CH_2OH \rightarrow C_6H_5.CHO \rightarrow C_6H_5.COOH$$

(3) By hydrolysis of the corresponding cyanides.

$$C_6H_5CN \rightarrow C_6H_5.COOH$$

### Properties of Aromatic Acids

The aromatic acids are generally crystalline solids, soluble in hot water, but sparingly soluble in cold water. The addition of dilute hydrochloric acid to cold solutions of their salts causes the acids to be precipitated.

### Benzoic Acid

Benzoic Acid ($C_6H_5.COOH$) occurs in gum benzoin, and in various balsams. When gum benzoin is heated, benzoic acid sublimes. It is also prepared synthetically from toluene. (Some benzoic acid is also obtained as a side product during the manufacture of benzaldehyde.) By passing chlorine into boiling toluene, benzotrichloride is prepared. This is then hydrolyzed with milk of lime, and calcium benzoate is formed.

$$C_6H_5.CCl_3 \rightarrow C_6H_5.C(OH)_3 \rightarrow C_6H_5.COOH \rightarrow (C_6H_5.COO)_2Ca$$

Benzaldehyde (formed by hydrolysis of benzal chloride present due to incomplete chlorination) is removed by distillation in steam, and the calcium benzoate is decomposed with dilute hydrochloric acid. The precipitated benzoic acid is further purified by recrystallization from hot water. During the chlorination of the toluene, it is possible that nuclear substitution as well as side chain substitution may take place. The benzoic acid formed would then contain chlorobenzoic acids as impurities.

$$ClC_6H_4CCl_3 \rightarrow ClC_6H_4.COOH$$

The amount of these chlorinated compounds is officially limited by a special test, which involves reacting on the acid with amyl alcohol and metallic sodium and thus converting the halide into sodium chloride which reacts with silver nitrate.

The benzoic acid obtained from natural sources may contain cinnamic acid. The oxidation of this substance to benzaldehyde by potassium permanganate enables its presence to be detected.

$$\begin{aligned} C_6H_5.CH{=}CH.COOH &+ 2O_2 \\ &= C_6H_5.CHO + 2CO_2 + H_2O \end{aligned}$$

Benzoic acid crystallizes in feathery crystals (m.p. 122°C). It is not very soluble in cold water, but dissolves more readily in hot water and in organic solvents. It is assayed officially by direct titration with alkali after solution in neutralized alcohol.

*Sodium Benzoate.* The official method of assay of this salt depends on the reaction with dilute acids, whereby benzoic acid is formed. Benzoic acid is sufficiently soluble in cold water to form a distinctly acid solution. Direct titration of Sodium Benzoate with standard acid would therefore not be practicable. Benzoic acid is much more soluble in organic solvents than in cold water, so that if ether is present during the titration, the greater part of the benzoic acid is dissolved in the ether, and only a small fraction is present in the water (p. 70). As most of the benzoic acid liberated during the titration is thus removed from the water layer, it is possible to titrate in accordance with the equation

$$2C_6H_5.COONa + H_2SO_4 = Na_2SO_4 + 2C_6H_5.COOH$$

The presence of excess sulphuric acid is indicated by a change in the colour of the indicator (bromophenol blue). In order to remove from the aqueous layer as much as possible of the liberated benzoic acid, the ether layer is removed just before the end-point is reached and replaced with fresh ether. The titration is then completed.

The official chloride and sulphate limit tests are carried out on Sodium Benzoate after removing by filtration the benzoic acid precipitated on acidifying.

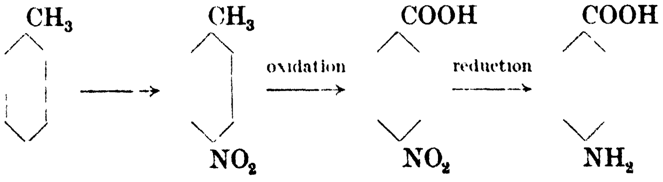
The sodium benzoate content of Caffeine and Sodium Benzoate is determined by removing the alkaloid, acidifying, extracting with ether, evaporating, and titrating the liberated benzoic acid with standard alkali.

*Benzyl Benzoate*, the ester of benzyl alcohol and benzoic acid, is assayed by the saponification method usually used for esters.

### DERIVATIVES OF BENZOIC ACID

*Benzoyl chloride*, which is the acid chloride of benzoic acid, is prepared by the action of phosphorus pentachloride on benzoic acid. It is an important reagent for the preparation of the esters of benzoic acid; *p.* nitro- and 3.5. dinitrobenzoyl chloride are used in the recognition of alcohols through ester formation.

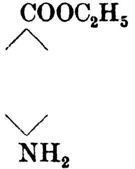
*p. Aminobenzoic acid* is obtained from toluene by the following series of reactions—



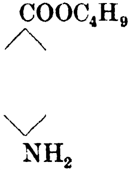
*Benzocaine* is the ethyl ester of this acid and is obtained by reducing the ester of the corresponding nitro-acid.

*Butyl Aminobenzoate* is the butyl ester, while *Procaine* and *Butacaine* are respectively the diethylamine derivative of benzocaine and the di-*n*-butylamine derivatives of propyl aminobenzoate. The last three substances are prepared from sodium aminobenzoate by reaction with the corresponding halide.

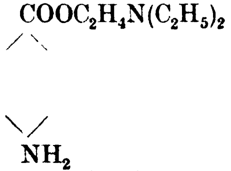
$$NH_2.C_6H_4.COONa + RCl = NH_2.C_6H_4.COOR + NaCl.$$



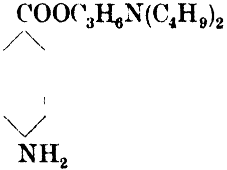
Benzocaine



Butyl aminobenzoate

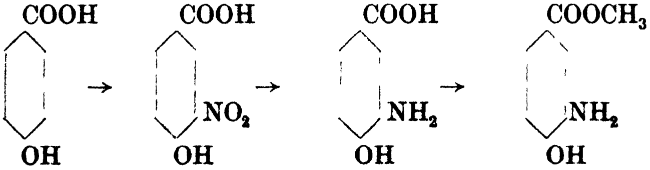


Procaine



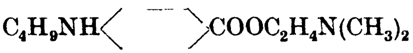
Butacaine

*Orthocaine* is the methyl ester of 3 amino 4 hydroxybenzoic acid. It is prepared as follows—



Orthocaine

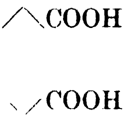
*Amethocaine* is a derivative of the procaine type, but it has the amino group substituted by the *n* butyl radical. The corresponding N-substituted acid has to be prepared and esterified.



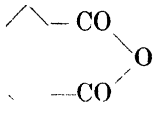
Amethocaine

## Dibasic Aromatic Acids

Phthalic acid (*o.* benzenedicarboxylic acid) is obtained by oxidation of naphthalene [e.g. by passing naphthalene vapour mixed with air over a heated catalyst (e.g. vanadium pentoxide)]. Owing to the proximity of the carboxyl groups of phthalic acid, anhydride formation takes place readily and phthalic anhydride is obtained. Phthalic acid is a dibasic acid. Its acid salt—potassium hydrogen phthalate—is often used for preparing buffer solutions of standard *p*H value.



Phthalic acid



Phthalic anhydride

## Unsaturated Aromatic Acids

The most important unsaturated aromatic acid is *cinnamic acid*, which occurs free or combined in various balsams. It may be prepared from benzaldehyde by condensation with sodium acetate in the presence of acetic anhydride, or by the reaction of benzal chloride with sodium acetate.

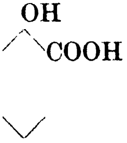
$$C_6H_5.CHO+CH_3.COONa = C_6H_5.CH=CH.COONa+H_2O$$

$$C_6H_5.CHCl_2+CH_3.COONa = C_6H_5.CH=CH.COONa+2HCl$$

The official method for the determination of balsamic acids depends on their conversion to potassium salts by boiling under a reflux condenser with alcoholic potash. Magnesium sulphate is added, and after filtration, the filtrate containing magnesium benzoate and cinnamate is acidified. The acids are separated from impurities by successive extraction with ether in acid solution, when the acids dissolve in the ether, and in very weakly alkaline solution, when the acids dissolve in the aqueous layer (cf. p. 577). Finally the acids are collected, dried in a vacuum desiccator over sulphuric acid, and weighed.

## Hydroxy Aromatic Acids

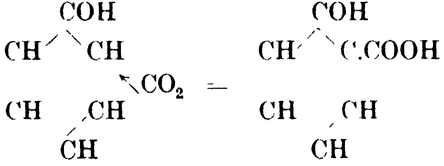
The most important of the three monohydroxy benzoic acids is the *ortho* derivative (salicylic acid).



Salicylic acid

*Salicylic Acid* occurs naturally as its methyl ester which is the chief constituent of oil of wintergreen. Salicylic acid may be prepared by the general methods, but it is usually obtained from phenol.

When sodium phenoxide is heated under pressure with carbon dioxide, sodium salicylate is formed. Salicylic acid is precipitated when the solution of the sodium salt is acidified. It forms colourless crystals (m.p. 159°C).



Salicylic Acid and Sodium Salicylate are officially assayed similarly to Benzoic Acid and Sodium Benzoate. The sodium salicylate content of Theobromine and Sodium Salicylate is determined in a like manner to sodium benzoate in Caffeine and Sodium Benzoate. The assay of Ointment of Salicylic acid depends on a bromination reaction (cf. assay of phenol, p. 515).

$$C_6H_4OH.COOH + 3Br_2 = 3HBr + C_6H_2Br_3OH + CO_2$$

Bismuth Salicylate (p. 215) is a basic salt of varying composition, prepared by double decomposition between bismuth nitrate and sodium salicylate.

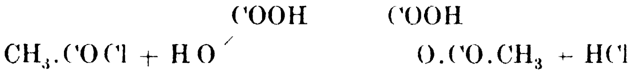
### DERIVATIVES OF SALICYLIC ACID

Salicylic acid forms esters, derived from the carboxyl group, which are prepared by the general methods. *Methyl salicylate* is prepared by the action of methyl alcohol on salicylic acid in the presence of sulphuric acid.

In the official assay of Methyl Salicylate, the total amounts of alkali required for saponification and for neutralization of the free acids are separately determined and the alkali actually reacting on the ester is found as the difference between these two values.

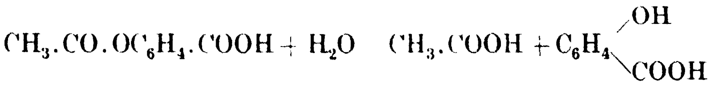
*Phenyl salicylate* (salol) is prepared by the reaction of phenol on salicylic acid in the presence of phosphorus oxychloride or carbonyl chloride which assists in the removal of water.

Derivatives can also be obtained from salicylic acid by reactions involving the phenolic hydroxyl group, e.g. acetyl chloride reacts with salicylic acid to form the acetyl derivative which is acetylsalicylic acid or aspirin.



$$\begin{array}{llll} & COOH & & COOH \\ CH_3.COCl + HO & & & O.CO.CH_3 + HCl \end{array}$$

*Acetylsalicylic Acid* is prepared by the action of acetic anhydride or acetyl chloride on salicylic acid, and is purified by recrystallization. Like other phenol esters, aspirin can be hydrolyzed to form acetic acid and salicylic acid.



$$CH_3.CO.OC_6H_4.COOH + H_2O \quad CH_3.COOH + C_6H_4\begin{matrix} OH \\ COOH \end{matrix}$$

This reaction serves as the basis of the official assay of Acetylsalicylic Acid. Acetylsalicylic Acid is boiled with excess standard alkali. After the hydrolysis is complete the excess alkali is determined by back titration with standard acid. A blank experiment is necessary to allow for loss of alkali by attack of the glass vessel.

$$\begin{aligned} & CH_3.CO.OC_6H_4.COOH + 2NaOH \\ & \qquad = CH_3.COONa + C_6H_4OH.COONa + H_2O \end{aligned}$$

Acetylsalicylic Acid is tested officially for the presence of salicylic acid. The test depends on the violet colour given by salicylic acid with a ferric salt solution and a colorimetric comparison is made with a solution of pure salicylic acid. For the assay of acetylsalicylic acid in Aspirin and Phenacetin Tablets and Compound Tablets of Codeine, the acid after extraction is hydrolyzed and the salicylic acid formed is determined by a bromination method (p. 526).

In Tablets of Aspirin and Dover's Powder, the aspirin is hydrolyzed, and extracted and weighed as salicylic acid.

*Mandelic Acid* ($C_6H_5.CHOH.COOH$) is an example of an aromatic acid containing an alcoholic hydroxyl group. The corresponding nitrile can be obtained by the regulated hydrolysis of amygdalin (p. 458), or synthetically from benzaldehyde.

$$\underset{\text{Amygdalin}}{C_6H_5.CH.(CN)—O—C_{12}H_{21}O_{10}} + 2H_2O$$
$$= \underset{\text{Mandelonitrile}}{C_6H_5.CHOH.CN} + 2C_6H_{12}O_6$$

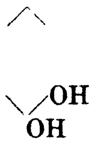
The manufacturing process involves the interaction of sodium cyanide and benzaldehyde sodium bisulphite followed by hydrolysis of the mandelo-nitrile thus prepared.

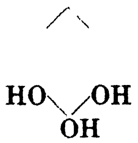
$$C_6H_5.CHOH.SO_3Na + NaCN = C_6H_5.CHOH.CN + Na_2SO_3$$
$$C_6H_5.CHOH.CN + 2H_2O = C_6H_5.CHOH.COONH_4$$

The official calcium salt is assayed on its calcium content (p. 257).

## Di- and Trihydroxy Acids

The most important di- and trihydroxy aromatic acids are 3.4. dihydroxybenzoic acid (protocatechuic acid) and 3.4.5. trihydroxybenzoic acid (gallic acid).


Protocatechuic acid


Gallic acid

*Gallic Acid* occurs in oak galls, tea and other plant products. It is usually obtained from tannin by hydrolysis with dilute acid. Ferric salts yield a blue-black precipitate with gallic acid. *Bismuth Subgallate* is a basic salt obtained by action with the acid on bismuth hydroxide.

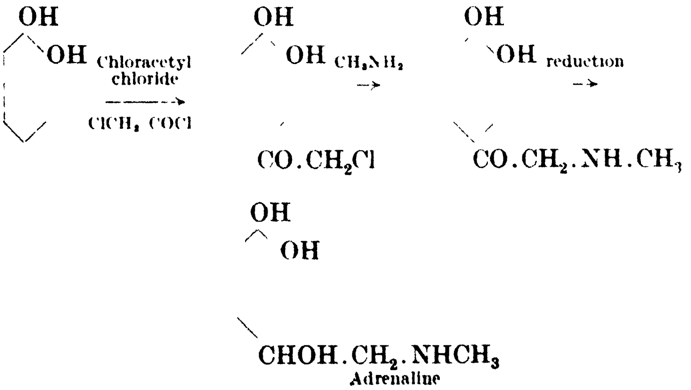
*The Tannins* are a group of vegetable products which possess the property of converting animal hides into leather. They are chemically rather indefinite. They are generally amorphous soluble substances with an astringent taste. They yield black precipitates with iron salts, and render gelatin and albumen insoluble. On hydrolysis certain tannins yield gallic acid and glucose, which suggests that chemically they partake of the nature of glucosides.

*Tannic Acid* is obtained from oak galls by extraction with ether after they have been subjected to a special fermentation. Commercial tannic acid is not a chemical individual, but a mixture. It is a pale yellowish substance with an astringent taste. It is soluble in water, and insoluble in organic solvents.

## THE AROMATIC SIDE-CHAIN AMINES

Aromatic side-chain amines have properties resembling the aliphatic amines (e.g. they are bases) and are prepared in corresponding ways.

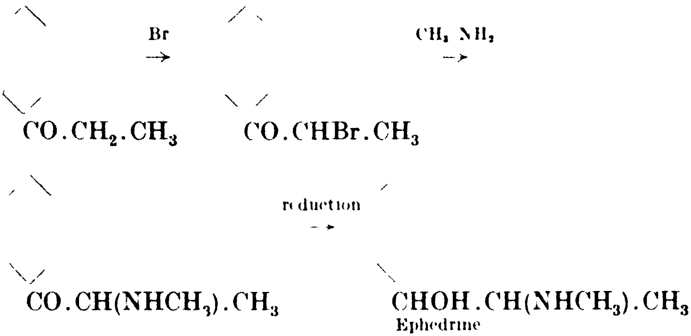
*Adrenaline*, the active principle of the suprarenal glands, is synthesized from catechol by the following series of reactions



The synthetic product thus obtained is optically inactive, but it may be resolved by crystallization of its *d*- tartaric acid salt.

The natural product is the laevo-rotatory form which is physiologically much more active than the dextro-rotatory form.

*Ephedrine,* which possesses a similar chemical structure to adrenaline, may be synthesized by the following series of reactions from phenylethyl ketone.



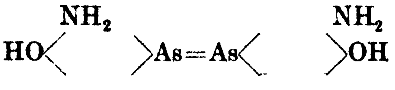
*Amphetamine* differs from the last two substances in not having an alcoholic as well as an amine group in the side chain. It is also a primary and not a secondary amine. It is obtained from the oxime of benzylmethyl ketone (phenylacetone).

$$C_6H_5.CH_2.CO.CH_3 \rightarrow C_6H_5.CH_2.C{=}NOH.CH_3$$
$$\rightarrow \underset{\text{Amphetamine}}{C_6H_5.CH_2.CHNH_2.CH_3}$$

## DERIVATIVES OF ARSENIC, ANTIMONY AND MERCURY

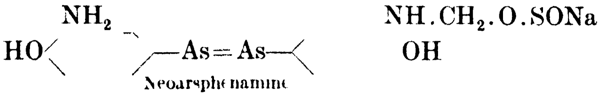
The organic arsenic derivatives are of two types, those with a structure comparable with that of the azo dyes with arsenic replacing nitrogen, and those derived from phenylarsonic acid. The arsphenamines belong to the former type.

*Arsphenamine* (salvarsan) has the formula

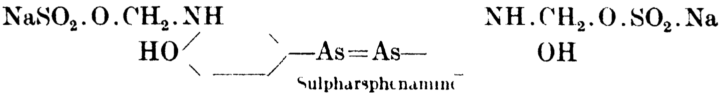


$$\overset{NH_2}{HO\langle\ \rangle}As{=}As\overset{NH_2}{\langle\ \rangle OH}$$

while the more soluble derivatives neoarsphenamine and sulpharsphenamine have the formulae

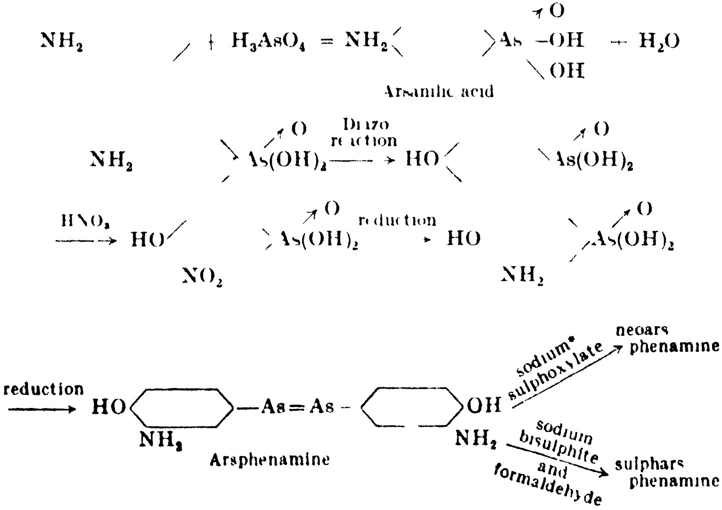


Neoarsphenamine

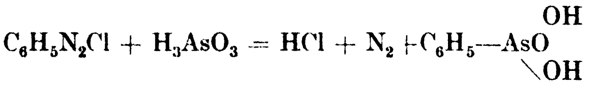


Sulpharsphenamine

Aniline reacts with arsenic acid to form *p* aminophenylarsonic acid (arsanilic acid) from which the above derivatives may be obtained in accordance with the following scheme—



*Phenylarsonic Acid* is obtained by the action of sodium arsenite on benzene diazonium salt solutions.



$$C_6H_5N_2Cl + H_3AsO_3 = HCl + N_2 + C_6H_5\text{—}\overset{OH}{\underset{\diagdown OH}{AsO}}$$

Phenylarsonic acid

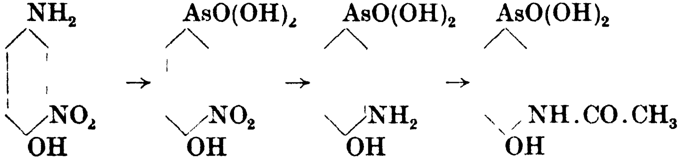
---

* Sodium sulphoxylate ($CH_2OH.SONa$) is obtained by reduction of formaldehyde sodium bisulphite.

*Carbarsone* is obtained from the *p.* amino derivative of this acid by reaction with urea

$$NH_2.CO.NH_2 + NH_2.C_6H_4.AsO(OH)_2$$
$$= NH_3 + \underset{\text{Carbarsone}}{NH_2.CO.NH.C_6H_4.AsO(OH)_2}$$

*Acetarsol* is the *p.* hydroxy *m.* acetylamino derivative of phenylarsonic acid; *p.* hydroxy *m.* nitraniline is diazotized and converted to the arsonic acid and subsequently the nitro group is reduced and acetylated.



Acetarsol

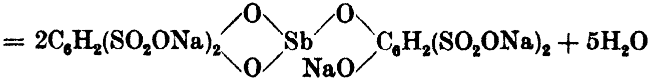
*Tryparsamide* is obtained from *p.* aminophenylarsonic acid by reacting on its sodium salt with the amide of chloracetic acid. The resulting acid is converted to its mono-sodium salt.

$$\underset{\text{Chloracetamide}}{NH_2.CO.CH_2Cl} + NH_2.C_6H_4.AsO(OH)_2$$
$$= NH_2.CO.CH_2.NH.C_6H_4.AsO(OH)_2$$

The arsenic in the official arsonic acid derivatives is assayed by treatment with fuming nitric acid which oxidizes the organic matter and converts the arsenic to arsenic acid. This is reduced by iodide to the arsenious state and, after removing the liberated iodine with thiosulphate, is titrated with standard iodine.

*Stibophen* is obtained by the action of antimony oxide and sodium hydroxide on sodium pyrocatechol 3.5. disulphonate. It differs from the arsonic acid derivatives in containing the metal in its lower valency state and thus it acts as a base to replace the hydrogen of three phenolic groups.

$$4C_6H_2(SO_2ONa)_2(OH)_2 + Sb_2O_3 + 2NaOH$$



$$= 2C_6H_2(SO_2ONa)_2\begin{matrix}\diagup O \diagdown \\ \diagdown O \diagup\end{matrix}Sb\begin{matrix}\diagup O \diagdown \\ \diagdown NaO \diagup\end{matrix}C_6H_2(SO_2ONa)_2 + 5H_2O$$

Stibophen

## THE MERCURY ORGANIC COMPOUNDS

These are of two main types: the di-alkyls (or aryls and the hydroxy alkyls (or aryls). The former result from the action of sodium amalgam on alkyl (or aryl) halides, and they can be used in synthetic processes, although they are less reactive than the zinc alkyls or the Grignard reagents (p. 474). The di-alkyls (or aryls) react with acids to give substances which are salts of the basic hydroxy alkyls (or aryls) (R—Hg—OH); thus, with mercury phenyl and nitric acid, the nitrate of phenyl hydroxy mercury is obtained

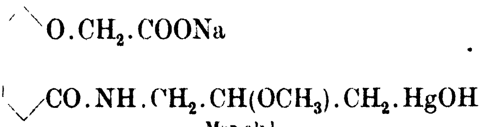
$$C_6H_5\text{—}Hg\text{—}C_6H_5 + HNO_3 = C_6H_5\text{—}Hg\text{—}NO_3 + C_6H_6$$

The official Phenylmercuric Nitrate is a basic salt containing equimolecular proportions of this salt and the free base ($C_6H_5$—Hg—OH). It is prepared by reacting on mercury phenyl with nitrogen dioxide at 0°C, followed by recrystallization from alcohol, during which partial hydrolysis occurs.

$$(C_6H_5)_2Hg + N_2O_4 = C_6H_5Hg.NO_3 + C_6H_5.NO$$

$$C_6H_5.Hg.NO_3 + H_2O = C_6H_5.Hg.OH + HNO_3$$

*Mersalyl* is a complex derivative of the hydroxy mercury alkyl type (R—Hg—OH), R being a salicylic acid amide derivative with the hydrogen of the hydroxyl group substituted by—$CH_2$.COONa and one of the hydrogen atoms of the amide group being replaced by methoxypropyl.



Mersalyl

The last two official substances are assayed for mercury by reduction to the metal, followed by solution in nitric acid and titration with ammonium thiocyanate.

# CHAPTER XXXI

# OTHER CARBON RING SYSTEMS

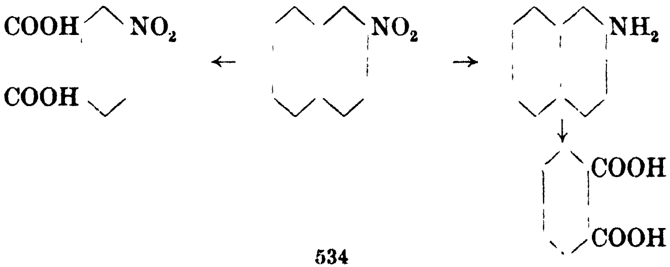
A LARGE number of compounds are known whose molecules are formed by the fusion of two or more benzene rings. When two rings are fused, naphthalene ($C_{10}H_8$) is obtained, while the molecules of anthracene and phenanthrene ($C_{14}H_{10}$) contain three benzene rings. Compounds are known containing more fused rings than this; in fact, the most complete example of ring fusion is found in graphite, which is composed of continuous sheets of fused six-membered rings stretching throughout the crystal (p. 220).

## NAPHTHALENE

Naphthalene is a constituent of coal tar, from which it is extracted (p. 488). The crystals deposited from the fraction containing naphthalene are purified by treatment with sulphuric acid, steam distillation, and finally sublimation. Naphthalene forms flat crystals, m.p. 81°C, with a characteristic smell.

### Formula of Naphthalene

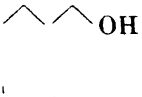
The constitutional formula of naphthalene was deduced from its behaviour on oxidation when it is converted to the benzene derivative, phthalic acid (p. 525). This proves that the molecule of naphthalene contains one benzene ring; the presence of the second was established by examining the behaviour of the nitro-derivative. This can be oxidized itself, when nitrophthalic acid is obtained, or reduced to the amino compound, which on oxidation gives phthalic acid without the amino group.



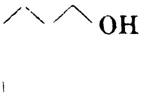
The formula has been confirmed by various syntheses from benzene compounds, e.g. from phenylvinylacetic acid, which gives a hydroxy naphthalene on heating; and this can be reduced to naphthalene itself.

## Properties of Naphthalene

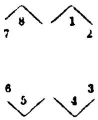
The properties of naphthalene and its derivatives are essentially those of aromatic compounds. Naphthalene reacts with nitric and sulphuric acids to form nitro- and sulphonic-acid derivatives; the hydroxy compounds are phenolic in character and the amines give the diazo reaction. However, one important difference from benzene lies in the number of isomeric derivatives which can be obtained, e.g. there are two mono-derivatives called α and β, and ten derivatives of the formula $C_{10}H_6X_2$ and fourteen of the type $C_{10}H_6XY$. The distinguishing nomenclature of these derivatives usually involves numbering as indicated, but the terms ortho, meta, and para are sometimes used for the cases where the two substituents are in the same benzene ring. The term *peri-* is sometimes used for the 1 8. derivatives



α naphthol



β naphthol



The orientation of the derivatives presented some difficulties, because of the large number of possibilities involved; but it was often solved by oxidation into phthalic acid derivatives.

*The Homologues of Naphthalene* are obtained by Friedel and Craft's reaction. They resemble the benzene homologues, e.g. on oxidation they yield carboxylic acids (naphthoic acids).

*The Naphthalene Sulphonic Acids* are obtained by the action of concentrated sulphuric acid. The proportions of the two isomers depends on the temperature of the reaction; below 80°C the α isomer predominates, above that temperature the β isomer.

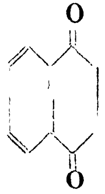
*The Naphthols* are prepared from the corresponding sulphonic acids by fusion with sodium hydroxide (cf. phenol, p. 511). Both isomers are present in coal-tar. While they generally resemble phenols, the hydroxyl group is somewhat more reactive, e.g. it is possible to prepare the amines from the naphthols. α naphthol, heated with the ammonia addition compound of zinc chloride, gives α naphthylamine, while β naphthylamine is obtained from β naphthol by passing ammonia and the amine vapour over a catalyst (aluminium).

*The Nitronaphthalenes.* Concentrated nitric acid nitrates naphthalene in the α position, but it is not so easy to prepare the β isomer. It can be done by nitrating α naphthylamine followed by removal of the amino group by the diazo reaction.

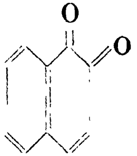
*The Naphthylamines* are prepared from the naphthols; or, in the case of the α isomer, from α nitronaphthalene by reduction. These bases are of considerable technical importance, especially in the dyestuffs industry.

*The Naphthaquinones* resemble benzoquinone in properties (p. 516). There are three of them.

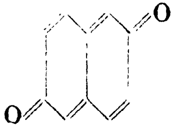
(α)



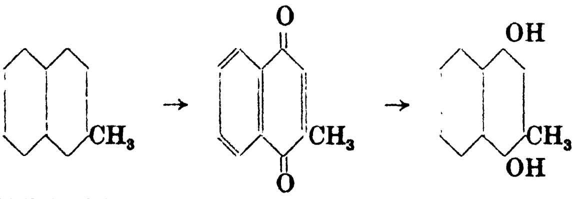
(β)



(amphi)

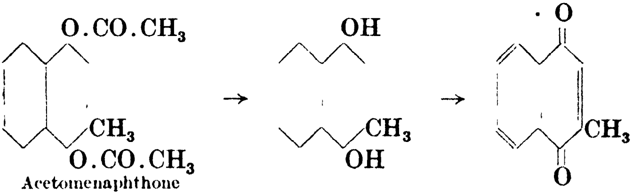


*Menaphthone* is the quinone of the first homologue of naphthalene (β methyl naphthalene, which is obtained from coal-tar). The hydrocarbon can be directly oxidized to the quinone by hydrogen peroxide or chromic acid. When the quinone is reduced (e.g. by titanous chloride, as in the official assay process) it forms the corresponding *para* dihydroxy phenolic compound.



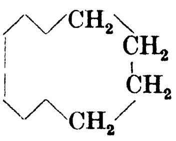
**β Methylnaphthalene** **Menaphthone** **Methyl naphthaquinol**

*Acetomenaphthone* is the di-acetyl derivative of the dihydroxy phenol obtained by reducing menaphthone. If the reduction is carried out by zinc and acetic acid in presence of acetic anhydride, the reduction product is acetylated as it is formed. The assay of Tablets of Acetomenaphthone depends on hydrolysis to the phenol, followed by quantitative oxidation to the quinone by ceric sulphate.

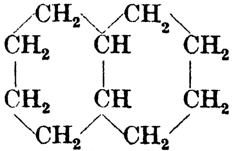


Acetomenaphthone

*The Hydro-naphthalenes* are obtained by direct hydrogenation in presence of a nickel catalyst. They are important industrial solvents, especially tetralin and decalin.



Tetralin



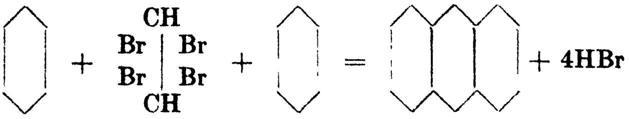
Decalin

## ANTHRACENE

Anthracene is obtained from coal-tar by fractional distillation. Basic impurities are removed by distilling from anhydrous potassium carbonate and the product is then treated with carbon disulphide which removes the soluble phenanthrene from the insoluble anthracene.

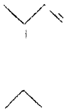
### Formula of Anthracene

The constitutional formula of anthracene was deduced from its analogy with naphthalene and by synthesis (Friedel and Craft's reaction) using a mixture of benzene and tetrabromoethane.

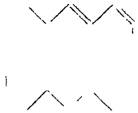


There is an important point to notice concerning this formula of three benzene rings fused side by side; it differs from benzene and naphthalene in that it cannot be represented fully by a Kekulé system of alternating double and single bonds (one ring will always be found to be of a non-Kekulé type).

Benzene



Naphthalene

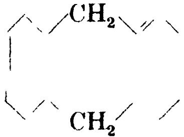


Anthracene

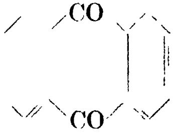
This accounts for certain differences in properties between anthracene and its derivatives and the naphthalene compounds which are less reactive.

## The Properties of Anthracene

The most significant difference between anthracene and naphthalene compounds lies in the ease with which the former adds on hydrogen (e.g. by reaction with sodium amalgam). The central ring is thus converted into a fully saturated system with the outer rings possessing Kekulé structures. A similar result is obtained by oxidation.



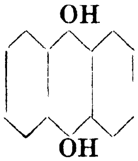
Dihydroanthracene



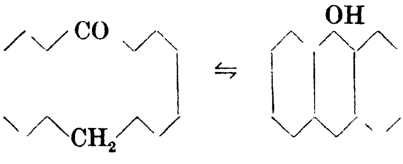
Anthraquinone

*Anthraquinone* is one of the most important derivatives of anthracene. It is obtained by the action of oxidizing agents on it (e.g. nitric acid oxidizes instead of nitrating; potassium dichromate and sulphuric acid is the usual oxidizing agent). Anthraquinone differs from the simpler quinones in its stability. It is unaffected by strong acids or by oxidizing substances. It is not easily reduced, but zinc and sodium hydroxide converts it to the quinol compound, while tin and acid reduces it to anthrone, which tautomerizes in the presence of alkali to anthranol. The presence of the carbonyl group in anthraquinone is demonstrated by the formation of an oxime.

Anthraquinone is commercially important as a first stage in the conversion of anthracene into the dyestuff, alizarin. Quinalizarin is a related compound.

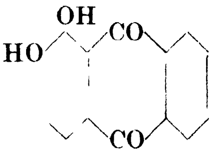


Anthraquinol

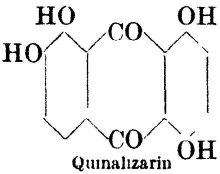


Anthrone

Anthranol

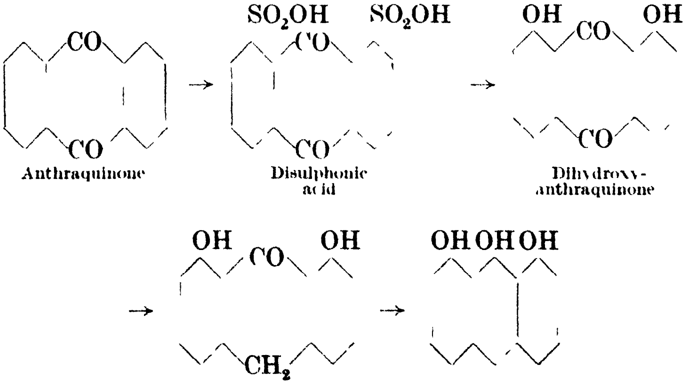


Alizarin



Quinalizarin

*Dithranol* is the 1.8. dihydroxy derivative of anthranol and it is prepared by reduction of the corresponding dihydroxy-anthraquinone, itself prepared from anthraquinone.



Anthraquinone

Disulphonic acid

Dihydroxy-anthraquinone

Dihydroxy-anthrone

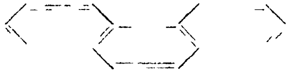
Dithranol

## PHENANTHRENE

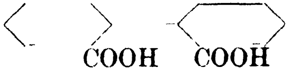
Phenanthrene is extracted from the anthracene fraction of the coal-tar distillate.

### Formula of Phenanthrene

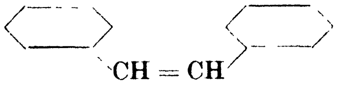
The constitutional formula of phenanthrene was deduced from its oxidation which proceeds through phenanthraquinone to diphenic acid which is a derivative of diphenyl $C_6H_5—C_6H_5$. It was confirmed by the transformation by heat of stilbene (diphenylethylene) into phenanthrene and by various other syntheses. It will be observed that (unlike anthracene) the constitution of phenanthrene can be fully represented by a Kekulé formula.



Phenanthrene

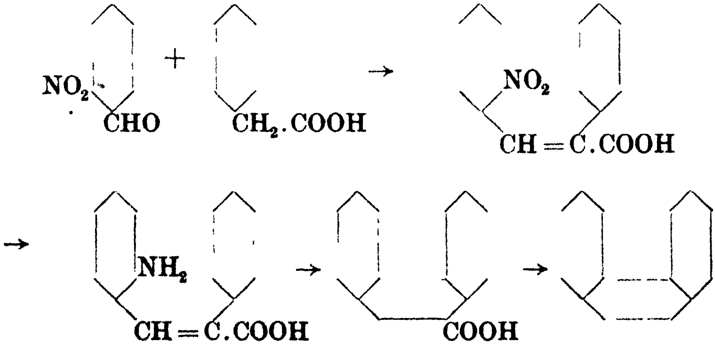


Diphenic acid



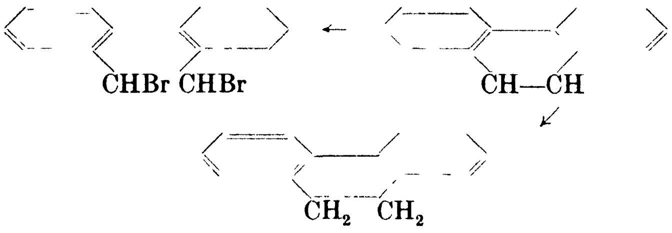
Stilbene

One phenanthrene synthesis starts from nitrobenzaldehyde and phenylacetic acid. The initial condensation product is converted to the diazo compound, which undergoes ring closure.



### Properties of Phenanthrene Compounds

Phenanthrene compounds are intermediate between the corresponding anthracene and naphthalene compounds, being less reactive than the former and more reactive than the latter. The two carbon atoms of the middle ring have some ethylenic qualities and, for example, they add on bromine or hydrogen.



The simpler phenanthrene compounds have not attained any considerable commercial importance. The substance is interesting, however, inasmuch as there are many natural plant and animal products which possess a similar or related skeleton of carbon atoms (e.g. resin acids, some alkaloids, sterols).

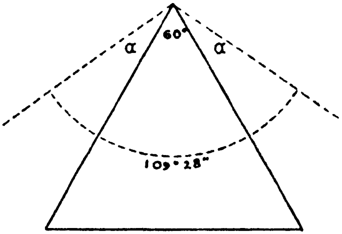
## ALICYCLIC RING COMPOUNDS

There is no reason why rings should possess double and single bonds as in benzene, naphthalene and other hydrocarbons of the aromatic type. Ring compounds are known where every bond is single, i.e. they are equivalent to an aliphatic chain of carbon atoms with the two ends joined together. Hydrocarbon compounds of this type are called the *cycloparaffins*, and they are the parent substances of the *alicyclic* (aliphatic-cyclic) compounds. In general the properties of the cycloparaffins resemble those of the straight chain paraffin hydrocarbons.

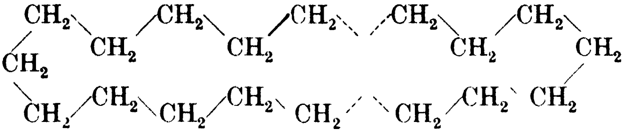
### Relative Stability of Alicyclic Ring Systems

It has been shown that the natural angles between the four valencies of a carbon atom is 109° 28′ (p. 420). Now if a co-planar symmetrical ring is formed there must be some alteration in these angles. The angles of the rings and the bending from the natural valency angles are given below and illustrated in the diagram which refers to a three-membered ring.

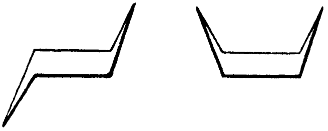
| No. of Atoms in Ring | Angle | Deviation of Valency Angle from Normal (α) | |
|---|---|---|---|
| 3 | 60 | 24° 44′ | |
| 4 | 90° | 9° 44′ | |
| 5 | 108° | 0° 44′ | |
| 6 | 120° | 5° 16′ | Deviation in opposite direction |
| 7 | 129° 26′ | 9° 59′ | |
| > 7 | > 129° 26′ | > 9° 59′ | |



It is clear that ring formation involves some strain in the carbon atom corresponding to the bending of its valency directions, and this strain is reflected in the relative stabilities of the various ring systems. The five and six ring systems are relatively stable, but the lower ones are less stable, i.e. the compounds with these rings are more reactive. Further, it will be seen that compounds with large rings should be heavily strained and therefore unstable. But in fact large cycloparaffin rings (e.g. $C_{20}H_{40}$) are known and are quite stable, because the carbon atoms are no longer arranged in a plane, but form zig-zag patterns just as in the open-chain compounds. Even the cyclohexane ring can exist in bent forms (i.e. strainless forms) and the existence of such forms gives rise to additional possibilities of isomerism as compared with the benzene ring system, which is invariably co-planar. The smaller cycloparaffin rings are also co-planar.



Large carbon atom strainless ring



Chair form Boat form

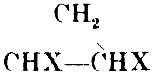
The strainless forms of the cyclohexane ring

## Isomerism in Alicylic Compounds

Apart from the question of non-planar configurations of the alicylic rings, geometrical isomerism and optical isomerism occur in these compounds, giving rise often to quite large numbers of isomerides.

The isomerism arises from the fact that the groups attached to the ring-forming carbon atoms are not coplanar with the ring as in the case of benzene, but are above and below it as a consequence of the tetrahedral distribution of the carbon valencies.

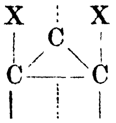
The simplest case occurs with the cyclopropane derivatives of the type

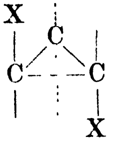


$$\overset{CH_2}{CHX—CHX}$$

where the diagram shows that there are two compounds of the same formula, differing in that the X groups are on the same side of the ring in one case and on opposite sides in the other. If X = COOH, the two compounds can be readily distinguished, for the cis compound forms an anhydride while the trans compound does not (cf. fumaric and maleic acids, p. 428).

It will further be noticed that while the cis molecule has a plane of symmetry, the trans molecule has no such plane, i.e. it is not superposable on its mirror image and therefore is capable of optical resolution.





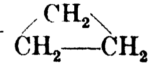
With the larger rings it is clear that the number of isomerides (both geometrical and optical) increases rapidly; e.g. there are eight isomerides of the formula $(CHX)_6$, one of which exhibits optical activity. The insecticide "Gammexane" is of this type (Hexachlorocyclohexane), and it is not yet known which of the possible isomers is the most potent compound.

## General Properties of Cycloparaffin

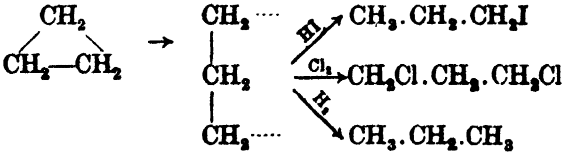
These compounds generally resemble the aliphatic rather than aromatic compounds, e.g. nitric and sulphuric acids oxidize and do not substitute. The various derivatives resemble the corresponding aliphatic compounds; the hydroxy compounds are alcoholic in type rather than phenolic and the amines resemble the aliphatic amines.

*Cyclopropane* (trimethylene) is prepared by the action of zinc on an alcoholic solution of dibromopropane, whereby the halogen atoms are removed; and this is followed by the chain ends joining together, forming a three-membered ring.

$Zn + BrCH_2.CH_2.CH_2Br = ZnBr_2 +$

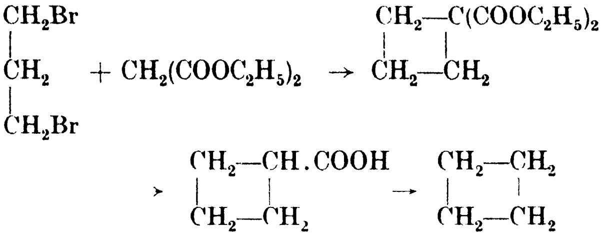


Cyclopropane is a gas at ordinary temperatures and pressures (b.p.—34·5°C.). The cyclopropane ring is unstable and is readily opened up, so that the cyclopropane compounds have many reactions reminiscent of unsaturated compounds; for example, they readily add on hydrogen, halogens and hydrogen halides. They are similarly absorbed by concentrated sulphuric acid, a property utilized in the assay of Cyclopropane.



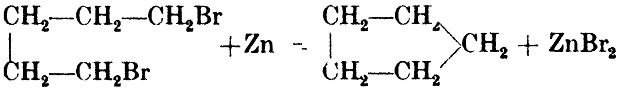
Cyclopropane differs from ethylenic unsaturated compounds in being unattacked by potassium permanganate solution in the cold; neither does it add on iodine monochloride. The last-named substance is used to control the quantity of ethylenic gases (e.g. propylene $CH_3.CH{=}CH_2$) in the official gas.

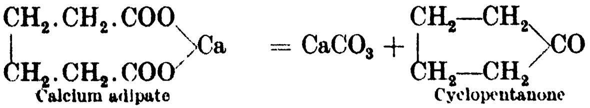
*Cyclobutane* $(CH_2)_4$ can be prepared from trimethylene dibromide (1.4. dibromopropane) by using a malonic ester synthesis process (p. 473).



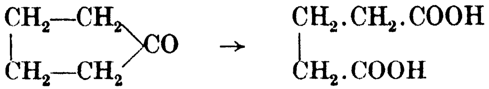
The four-membered ring contained in this substance and its derivatives is more stable than the three-membered ring of cyclopropane and it does not readily add on hydrogen halides or halogens. Hydrogen can be added in presence of a catalyst —forming *n* butane as a result of ring opening.

*Cyclopentane* is present in petroleum in small quantities. It is prepared from 1.5. dibromopentane by the action of zinc. A ketone (cyclopentanone) is obtained from the calcium salt of adipic acid by distillation.





The five-membered cyclopentane ring is stable and the compounds therefore have no unsaturated properties. The ring is opened up only by high temperature catalytic hydrogenation, or by processes involving special substituent groups, e.g. oxidation of ketones which breaks an open chain into two fragments, opens a five-membered ring.

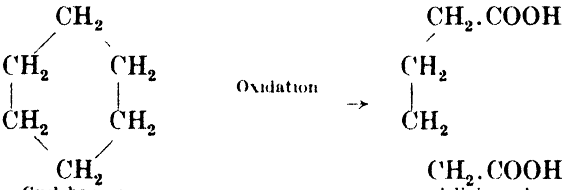


*Cyclohexane* is a constituent of Russian petroleum. It is prepared by the catalytic hydrogenation of benzene, and its derivatives are prepared from benzene substitution products by the same reaction, e.g. the hydrogenation of phenol yields cyclohexanol.

$$C_6H_6 + 3H_2 = C_6H_{12}$$

$$C_6H_5OH + 3H_2 = C_6H_{11}OH$$

The six-membered ring is stable. The ring is not opened by hydrogen, hydrogen halide or halogens, but cyclohexane is converted to adipic acid by potassium permanganate. Dehydrogenating reagents convert cyclohexane and its derivatives into the corresponding benzene compounds.

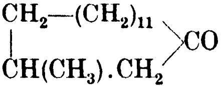


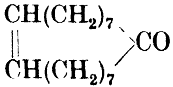
Cyclohexane Adipic acid

## MANY-MEMBERED CARBON RINGS

By heating the calcium or thorium salts of long chain di-basic acids, it is possible to prepare the ketones derived from cycloparaffins with many methylene groups forming the ring system (cf. formation of cyclopentanone from calcium adipate). The natural odoriferous products, muscone ($C_{16}H_{30}O$) and civetone ($C_{17}H_{30}O$) are ketones of this type.

$$(CH_2)_n(COO)_2Ca = (CH_2)_nCO + CaCO_3$$


Muscone


Civetone

The many-membered ring compounds are stable and the rings are not opened by the usual reagents. Their heats of combustion are the same as for open chain paraffins, and X-ray crystal analysis methods have shown that the rings are distorted, so that most of the molecule consists of two chains lying beside and parallel to one another (cf. p. 314).

## THE TERPENES

The saps and tissues of certain plants contain oils which may be obtained by expression, extraction in a solvent, or by low pressure or steam distillation. These "essential oils" carry the characteristic odour of the plant product, and in many cases they consist of hydrocarbons, called terpenes, or of simple products derived from these hydrocarbons. The terpene hydrocarbons are closely related to the cycloparaffins, being in many cases their ethylenic derivatives.

The first group of terpenes which were investigated consists of isomeric substances of the formula $C_{10}H_{16}$, and these became known as the monoterpenes. Subsequently other groups were discovered and were named accordingly.

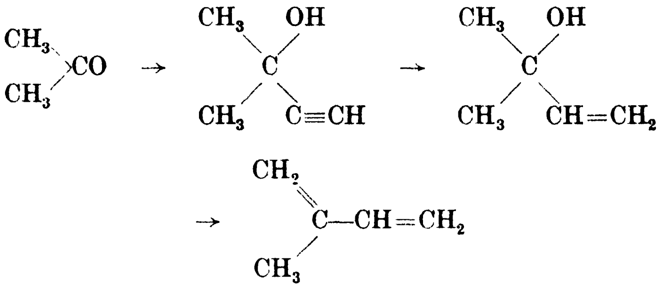
| | | | |
|---|---|---|---|
| $C_5H_8$ | Hemiterpenes | $C_{15}H_{24}$ | Sesquiterpenes |
| $C_{10}H_{16}$ | Monoterpenes | $C_{20}H_{32}$ | Diterpenes |
| $C_{30}H_{48}$ | Triterpenes | | |

Thus the general formula of all the compounds can be represented by $(C_5H_8)_n$, and rubber ($n$ = several hundred) can also be regarded as a terpene, although one of high molecular weight.

### The Hemiterpenes

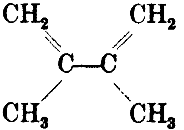
The important hemiterpene is isoprene and the structure of isoprene is the basis of the structures of the more complex terpenes. Isoprene is obtained by the dry distillation of rubber and by the action of heat on the vapour of limonene, which is a monoterpene.

The constitution of isoprene shows that it consists of a branched chain hydrocarbon containing a pair of conjugated double bonds, as can be seen from the following synthesis, which is of commercial importance. The sodium derivative of acetone can be condensed with acetylene, the product on reduction and then dehydration gives isoprene.



Isoprene

The most important derivative of isoprene is dimethylbutadiene (methylisoprene), which is polymerized to make a synthetic rubber-like substance. (Other rubber substitutes are obtained by polymerizing butadiene and chloroprene.)



Dimethyl butadiene

$CH_2{=}CH{-}CH{=}CH_2$
Butadiene

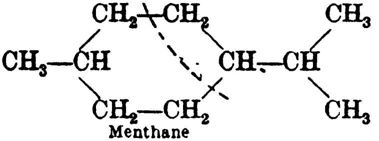
$CH_2{=}CH{-}CCl{=}CH_2$
Chloroprene

## The Monoterpenes

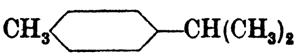
The isomeric monoterpenes are of three types: (*a*) monocyclic, (*b*) dicyclic, and (*c*) olefinic or open chain. The most important compounds of the first type are limonene (oil of orange and other citrus fruits, caraway, etc.), and terpineol (cardamon oil). Dicyclic terpenes include pinene (oil of turpentine), and camphor is a related oxygen compound.

The open-chain monoterpenes themselves are less important than their oxygen derivatives such as citronellal (oil of citronella), citral (oil of lemon grass and oil of lemon).

The parent saturated hydrocarbon of the monoterpenes is menthane ($C_{10}H_{20}$), which contains a six-membered ring (methyl isopropyl cyclohexane), and can be dehydrogenated to the corresponding benzenoid derivative, *p.* cymene. The division of the menthane molecule shows how the carbon atom skeleton is based on the co-existence of two isoprene units.

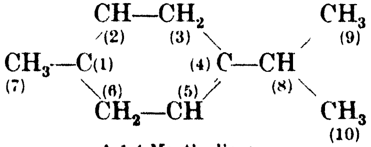


Menthane

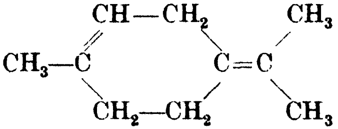


*p.* Cymene

The monocyclic terpenes differ from menthane in possessing two double bonds. There are fourteen different arrangements of two such bonds in the menthane molecule. They are distinguished by numbering and using the Δ sign to indicate the position of the double bond, thus Δ 1, 4 means double bonds between carbon atoms 1 and 2, and 4 and 5. (If the double bond does not pass from one number to the next higher number, both ends of the bond must be indicated, thus Δ 1, 4 (8) means that the second bond lies between carbon atoms 4 and 8. The systematic name for these monocyclic terpenes is menthadienes.



Δ 1,4 Menthadiene

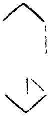


Δ 1,4(8) Menthadiene

It should be observed that the double bonds alter their positions fairly readily in these compounds.

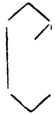
The dicyclic terpenes, as their name implies, contain two ring systems. These are not fused as in the case of naphthalene, but the smaller ring bridges across the larger, which is a cyclohexane ring. The diagrams show that the smaller ring can be three-, four-, or five-membered (cyclopropane, cyclobutane or cyclopentane). The dicyclic terpenes contain only one double bond, but their carbon atoms are arranged in the same way as for the monocyclic terpenes.

Cyclohexane + cyclopropane



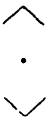
Carane type

Cyclohexane + cyclobutane



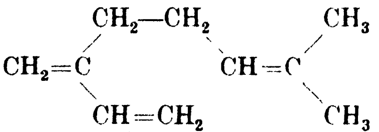
Pinane type

Cyclohexane + cyclopentane



Camphane type

The olefinic terpenes, although they have an open-chain structure with three double bonds, have essentially the same arrangement of carbon atoms as the other terpenes, as can be shown by writing their formulae in accordance with the proper valency directions of the carbon atoms.



Myrcene

## General Properties of Monoterpenes

The monoterpenes are liquids whose chemical reactions fall into two types, because they are intermediate in hydrogen content between the fully saturated menthane and the Kekulé (three-double-bonded) benzene hydrocarbon, cymene—

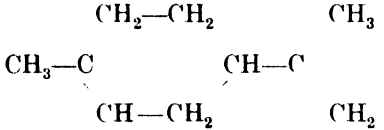
(1) They behave as ethylenic unsaturated substances and add on halogens, nitrosyl chloride, etc.

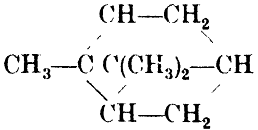
(2) Hydrogen can be removed by treatment with iodine or sulphur, or by first adding on bromine and then removing hydrogen bromide with alcoholic potash. *p.* Cymene is obtained.

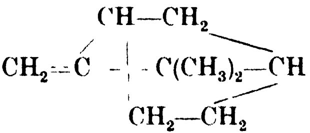
*Limonene* is one of the most important monocyclic monoterpenes. It is optically active owing to the presence of an asymmetric carbon atom. The racemic form is known as dipentene, an important constituent of pine oil.

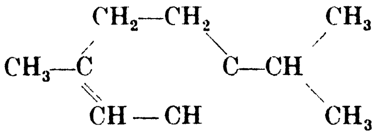
*Pinene* is contained in "oil of turpentine," which is the product obtained by steam-distilling the resin exuded from pine trees. It contains a four-membered ring bridging the six-membered ring. When it is heated in an autoclave with a suitable catalyst a molecular rearrangement occurs, leading to the production of camphene, which has a different ring system (two five-membered rings). The production of camphene is important commercially, since synthetic camphor is obtained from it by oxidation with chromic acid.

*The Terpinenes* are monocyclic terpenes. There are three isomeric substances which occur together in various essential oils. They differ in the positions of the double bonds ($\Delta$ 1, 3; $\Delta$ 1, 4; and $\Delta$ 1(7), 3 menthadienes.


Limonene or Dipentene

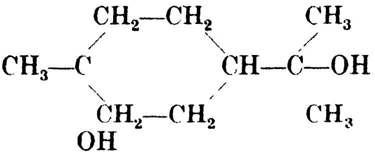

Pinene


Camphene

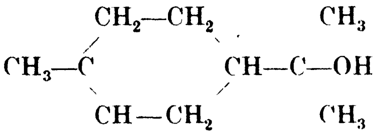

$\Delta$ 1, 3 Terpinene

*Terpin* is a saturated dihydroxy alcohol which is obtained by adding a molecule of water on to each of the double bonds of limonene. It is also obtainable from pinene by ring-breaking followed by the addition of water. It is prepared from turpentine oil by a hydration reaction involving treatment with dilute sulphuric acid. The substance then contains *terpin hydrate* ($C_{10}H_{20}O_2$, $H_2O$).

*Terpineol* is an unsaturated monohydroxy alcohol intermediate between limonene and terpin and is obtained by a catalytic dehydration of terpin hydrate.



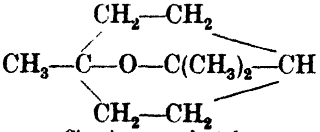
Terpin



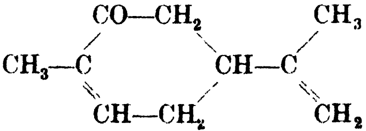
Terpineol

*Cineole* (*Eucalyptol*) occurs in eucalyptus and cajaput oils and is an ether derived from terpin, ether formation occurring between the two hydroxyl groups in the terpin molecule, forming a bridging ring.

*Carvone* is an unsaturated ketone, related to limonene, which is found in various essential oils, notably oil of caraway and oil of dill. The carvone content of these oils is determined by adding hydroxylamine hydrochloride and titrating the acid liberated on oxime formation with standard alkali.



Cineole or eucalyptol



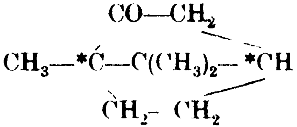
Carvone

$$C_9H_{14}CO + NH_2OH, HCl \rightarrow C_9H_{14}C{=}NOH + HCl + H_2O$$

*Camphor* is obtained from the camphor tree or synthetically from the pinene of oil of turpentine (p. 551). It is a saturated ketone with a five-membered ring bridging a six-membered ring, and is therefore related to the camphane type of dicyclic terpenes. It contains two asymmetric carbon atoms which are not equivalent, so that there are four possible optical isomers, only two of which are known. The asymmetric atoms are shown thus *.

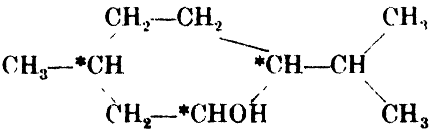
The properties of camphor are in keeping with its constitutional formula. Since it is saturated, it does not form addition compounds. It is a ketone. (The conversion to its dinitrophenylhydrazone forms the basis of its official assay). The presence of a $CH_2.CO$ grouping is evidenced by the formation of an isonitroso derivative, which fact was important during the work which led to the final elucidation of its structure.

$$—CO.CH_2— + HNO_2 \rightarrow —CO.C{=}NOH— + H_2O$$



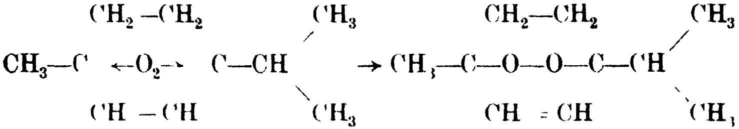
Camphor

*Menthol* is a saturated alcohol found in oil of peppermint, or obtained synthetically by hydrogenation of the corresponding benzene compound, thymol. Menthol contains three asymmetric carbon atoms, and thus there are eight optical isomers.



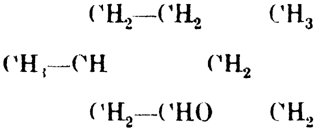
Menthol

*Ascaridole*, which occurs in oil of chenopodium, is a peroxide in which the peroxide group forms a bridging ring. Its relation to the monocyclic terpenes is shown by the method of oxygen addition to a conjugated double bond system. A similar reaction has been established in other cases.

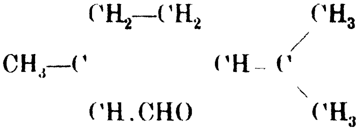


Ascaridole

*Citronellal* and *Citral* (or *Geranial*) are aldehydes of the olefinic terpene series. Citral has a strong odour of lemons. It is also commercially important because it can be converted into a substance with a strong violet-like odour



Citronellal



Citral

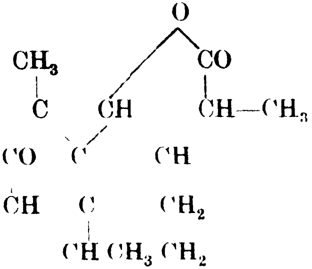
## The Sesquiterpenes and Higher Terpenes

These have not been as fully worked out as the simpler terpenes. They include structures of the olefinic or open chain, monocyclic and dicyclic types, the latter having bridged ring systems. There are sesquiterpenes which bear the same relation to naphthalene compounds as the monoterpenes bear to benzene derivatives, and the diterpenes may be similarly related to phenanthrene.

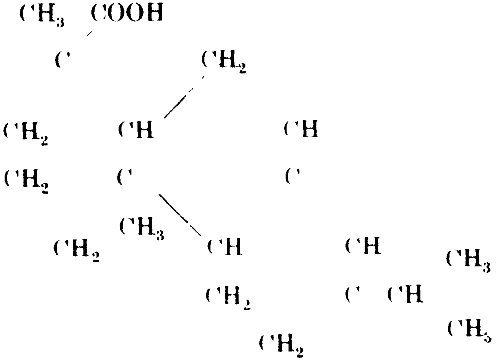
*Santonin* is the lactone of a hydroxy acid related to a sesquiterpene.

*Abietic Acid* ($C_{20}H_{30}O_2$) is the most important resin acid and is obtained from colophony resin by distillation. It is probably not present as such in the original resin but is formed during the extraction. Abietic acid bears a close relation to the phenanthrene hydrocarbon retene ($C_{18}H_{18}$).

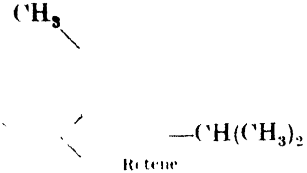
*Squalene* is the most important triterpene, while *Carotene* and *Vitamin A* are of the $C_{40}$ and $C_{20}$ groups respectively. The first-named substance is of the olefinic type; but both carotene and vitamin A have ring and olefinic groupings within the same molecule.



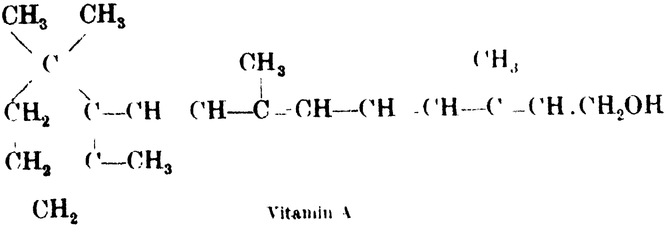
Santonin



Abietic acid



Retene



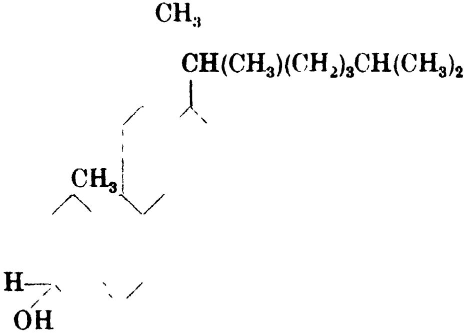
Vitamin A

## THE STEROLS

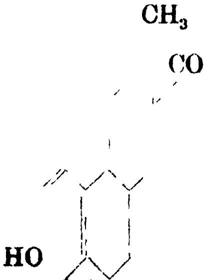
The sterols include a group of plant and animal products whose molecular structures are based upon a single pattern of carbon atom rings. They include substances such as cholesterol ($C_{27}H_{45}OH$), calciferol ($C_{28}H_{43}OH$), the bile acids, the sex hormones and derivatives obtained from the glycosides of digitalis, strophanthus and the saponins.

The essential structure of the sterols consists of three rings fused (as in phenanthrene) with an additional five-membered carbon ring. The sterols contain some double bonds, but the structures are for the most part saturated and not benzenoid. Thus there are many possible geometrical and optical isomers. The oxygen which is usually present may be alcoholic, ketonic, or carboxylic.

Ring system of sterols



Cholesterol*



Oestrone*

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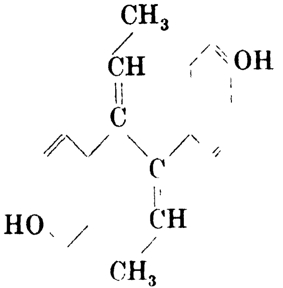
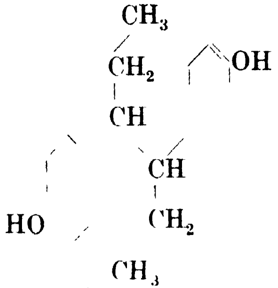
* In these formulæ the carbon and the hydrogen atoms of the ring system have generally been omitted.

Attempts have been made to prepare simplified molecules based on the sterolic structures and some of the compounds thus obtained have become important in medicine. *Dienoestrol*, *Hexoestrol*, and *Stilboestrol* are of this type



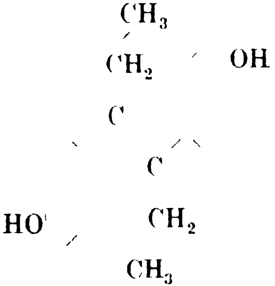
Dienoestrol

[$C_6H_4OH\ C(=C_2H_4)\ C(=C_2H_4)\ C_6H_4OH$]



Hexoestrol

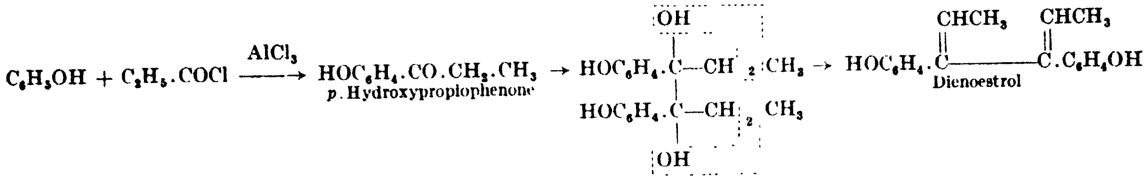
[$C_6H_4OH\ CH(C_2H_5)\ CH(C_2H_5)\ C_6H_4OH$]

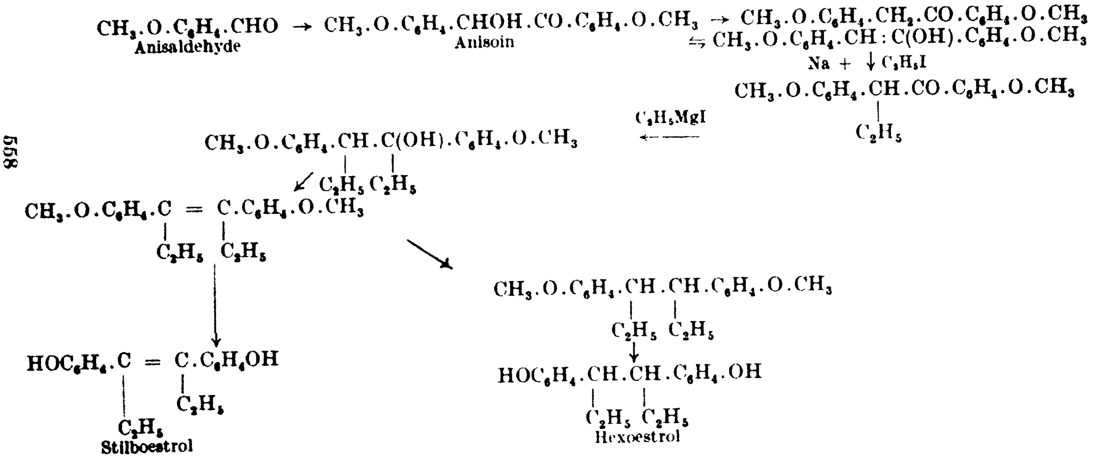


Stilboestrol

[$C_6H_4OH.C(C_2H_5)=C(C_2H_5)C_6H_4OH$]

These three substances (which are officially assayed by a gravimetric method involving acetylation of the phenolic hydroxyl groups and weighing the acetylated product) are prepared by the following series of reactions.


$C_6H_5OH + C_2H_5.COCl \xrightarrow{AlCl_3} HOC_6H_4.CO.CH_2.CH_3$
p. Hydroxypropiophenone
OH
OH
Dienoestrol


$CH_3.O.C_6H_4.CHO \rightarrow CH_3.O.C_6H_4.CHOH.CO.C_6H_4.O.CH_3 \rightarrow CH_3.O.C_6H_4.CH_2.CO.C_6H_4.O.CH_3$
Anisaldehyde
Anisoin
$\leftrightarrows CH_3.O.C_6H_4.CH:C(OH).C_6H_4.O.CH_3$
Na + $C_2H_5I$
$C_2H_5MgI$
Stilboestrol
Hexoestrol

## CHAPTER XXXII

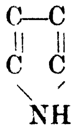
# THE HETEROCYCLIC COMPOUNDS

For the most part, the compounds which have been described in the earlier chapters have contained ring systems composed of carbon atoms only. It is possible for other elements (notably nitrogen, oxygen and sulphur) to replace the carbon atoms of these rings to form a ring containing the foreign atom. Compounds containing rings of this type are called *heterocyclic compounds* to distinguish them from the homocyclic compounds in which the rings contain carbon atoms only. A few heterocyclic compounds have been mentioned already (e.g. oxygen ring compounds such as lactones and sugars; nitrogen ring compounds such as the ureides and purines). This chapter deals with the remaining compounds containing heterocyclic rings, the rings containing nitrogen being the most important.

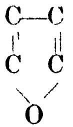
## Nomenclature of the Heterocyclic Rings

Nitrogen, oxygen, and sulphur can replace carbon in five- or six-membered rings; more than one carbon atom can be replaced. The products thus obtained are generally of the aromatic rather than the aliphatic type, but aliphatic type compounds containing the same skeletons of atoms are known.

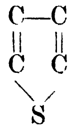
The five-membered rings with one carbon atom replaced are—



Pyrrole type

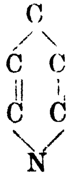


Furan type

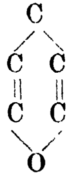


Thiophene type

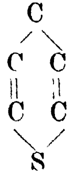
The six-membered rings with one carbon atom replaced are—



Pyridine type

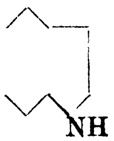


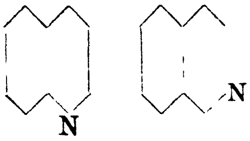
Pyran type

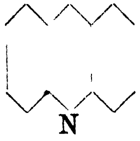


Thiopyran type

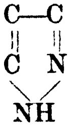
These rings may fuse with one another or with carbon rings to produce other important series of compounds, e.g. the following—

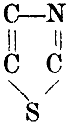

Indole
Benzene + Pyrrole

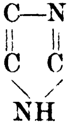

Quinoline and Isoquinoline
Benzene + Pyridine


Acridine

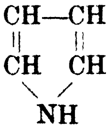
Among the important ring systems with more than one carbon atom replaced, there are the following—

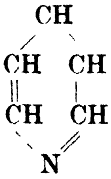

Pyrazole


Thiazole


Imidazole or glyoxaline

In each case, the ring has been named from the simplest compound containing it, i.e. with the carbon atoms of the ring united with hydrogen in accordance with its normal quadrivalency. Thus pyrrole and pyridine are compounds of formulae—


Pyrrole


Pyridine

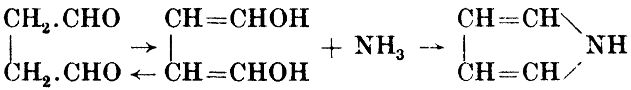
## FIVE-MEMBERED HETEROCYCLIC RING SYSTEMS

**Pyrrole is the most important of the three simpler five-membered heterocyclic ring systems. This ring occurs in many complicated natural products such as haemoglobin, chlorophyll and many alkaloids.**

Pyrrole, furan and thiophene resemble benzene in physical and many chemical properties; their derivatives often resemble the corresponding derivatives of benzene.

## Pyrrole

Pyrrole occurs in the oil obtained by the destructive distillation of bones (bone oil) and it is obtained from this oil. In the laboratory it can be prepared by a reaction which serves to confirm its constitution, the action of ammonia on the di-aldehyde corresponding to succinic acid. By using ketones of the type $R.CO.CH_2.CH_2.CO.R$ derivatives of pyrrole may be obtained.

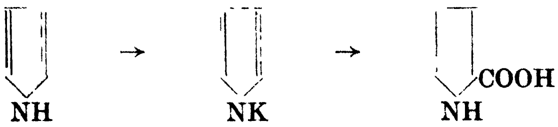


Pyrrole is a colourless liquid which discolours on standing in contact with air and becomes a resinous mass. Acids also cause resinification, but pyrrole is stable to alkalis.

### Chemical Properties of Pyrrole and its Derivatives

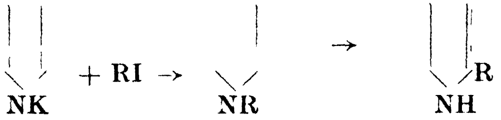
(1) Pyrrole contains an imino group (NH) but has few basic qualities and does not form ammonium type salts by addition of acids.

(2) Instead, the hydrogen of the imino group has an acid function and is replaceable by metallic potassium. In this respect, the NH group of pyrrole resembles the OH group of phenols. Correspondingly, the potassium salt is converted into the salt of the α carboxylic acid by heating in an atmosphere of carbon dioxide (cf. formation of salicylic acid from sodium phenate) and pyrrole couples with diazo compounds as do the phenols, dyestuffs being obtained.



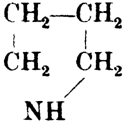
(3) Alkyl groups can be substituted for the hydrogen on the nitrogen atom by reacting with alkyl halides on the potassium

derivative. The N derivatives thus obtained are changed by heating, as the alkyl group migrates from the nitrogen on to a carbon atom of the ring.

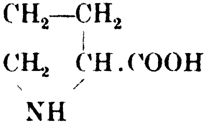


(4) Pyrrole compounds are generally aromatic in nature; but, owing to the resinification caused by acids, it is not possible to sulphonate or nitrate them. Halogens substitute and do not form addition compounds.

(5) Hydrogen can be added on to the pyrrole molecule to form successively a dihydro derivative and then the fully hydrogenated derivative, which is called *pyrrolidine*. Pyrrolidine derivatives occur in proteins and alkaloids (p. 576), e.g $\alpha$ pyrrolidine carboxylic acid is the amino-acid, known as *proline*.



Pyrrolidine

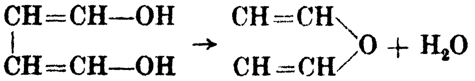


Proline

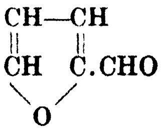
(6) On heating with chloroform and sodium ethoxide, the pyrrole ring can be converted into the pyridine ring system.

## Other Ring Systems

*Furan* and its derivatives are obtained by the dehydration of diketones of the type used for the preparation of pyrrole compounds (1.4. diketones), the furan ring being formed by dehydration. The most important furan derivative is furfuraldehyde.



Furan



Furfuraldehyde

*Furfuraldehyde* is obtained from pentose sugars by heating them with dilute mineral acids. It is manufactured by heating bran with dilute sulphuric acid. Furfuraldehyde resembles benzaldehyde in many reactions; for example—

(*a*) It undergoes self oxidation and reduction to a mixture of the corresponding acid and alcohol.

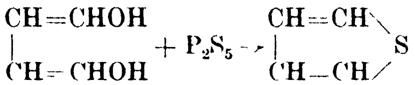
(*b*) It gives furfuramide (which resembles hydrobenzamide) with ammonia.

(*c*) It undergoes the benzoin conversion to form furfuroin.

(*d*) It condenses with acids to form unsaturated acids.

*Thiophene* is present in the benzene extracted from coal tar and is not easily removed from it. It is somewhat more readily sulphonated than benzene, and the extraction process is based on treatment with concentrated sulphuric acid. Thiophene can be regenerated from the sulphonic acid by treatment with steam.

The homologues of thiophene are obtained from 1.4. diketones by treatment with phosphorus pentasulphide (cf. preparation of pyrrole).

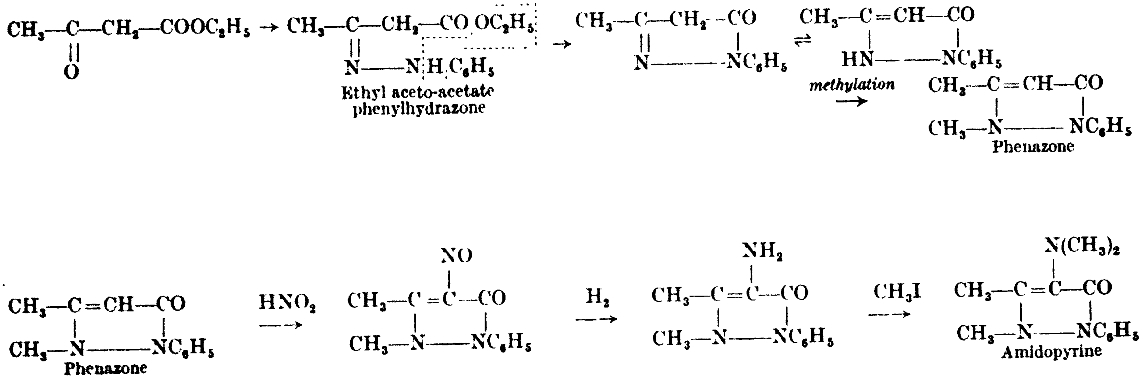


Thiophene is more definitely aromatic than pyrrole or furan and is readily substituted by halogens, sulphuric acid or nitric acid. The sulphonic acids and the nitro compounds resemble the corresponding benzene compounds and, similarly, the hydroxy compounds have phenolic properties. The amines, however, do not give the diazo reaction.

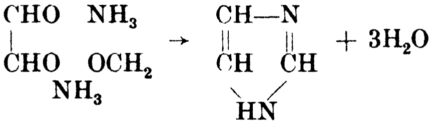
*Pyrazole.* The derivatives of pyrazole are obtained from ethyl aceto-acetate by reaction with hydrazine. This reaction yields the ketones of the series called *pyrazolones*. The pyrazole compounds are more stable than the pyrroles and do not change into resinous masses. They are weakly basic and their salts are decomposed by water.

*Phenazone* and *Amidopyrine* are prepared by the series of reactions as shown on p. 564.

*Imidazole* (also known as *Glyoxaline*). Compounds containing this ring system occur in many natural products. The parent substance is obtained by the action of glyoxal,


Ethyl aceto-acetate phenylhydrazone
methylation
Phenazone
Phenazone
HNO₂
H₂
CH₃I
Amidopyrine

formaldehyde, and ammonia (hence the second name) and the reaction can be adapted for the preparation of the derivatives by using other 1.2. di-aldehydes or ketones.

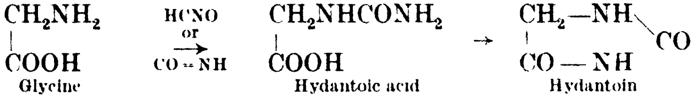


The imidazoles are more strongly basic than the pyrroles and form stable salts. They are also acidic in that the N hydrogen atom can be replaced by metallic potassium.

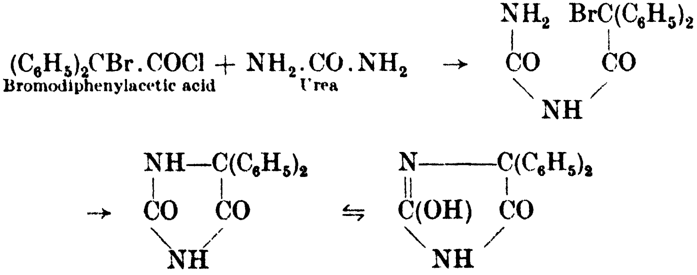
*Histidine* is an important protein amino-acid derived from glyoxaline. It can be changed by the action of acids or by bacterial action into histamine, which is also prepared synthetically as shown on p. 566.

*Histamine Acid Phosphate* is obtained by the action of phosphoric acid on histamine.

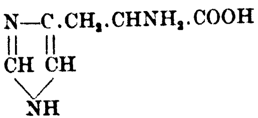
*Hydantoin* is a ureide type of diketone related to a hydrogenated glyoxaline. It is prepared by the action of glycine on potassium cyanate, followed by removal of a molecule of water from the product by treatment with acid.



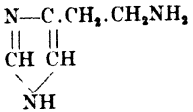
*Phenytoin* is a diphenyl derivative of hydantoin, prepared by the following series of reactions.



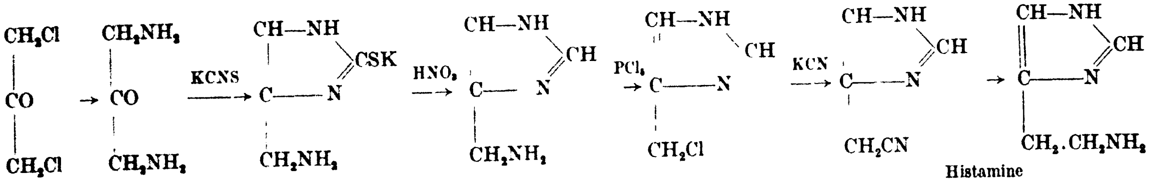
Phenytoin



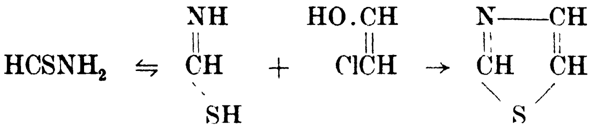
Histidine



Histamine



*Thiazole.* Thiazole can be prepared by the action of thioformamide on chloracetaldehyde. Thiazole compounds generally resemble pyridine compounds. They are characterized by great stability, being unattacked even by hot nitric acid or by reducing agents.



Thioformamide Chloracetaldehyde Thiazole

## SIX-MEMBERED HETEROCYCLIC RING COMPOUNDS

The most important six-membered heterocyclic ring contains one nitrogen atom. In its aromatic form, this ring system is found in pyridine and its derivatives. The corresponding fully saturated compound is called piperidine.

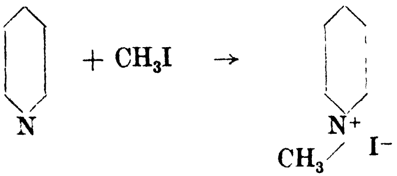
### Pyridine

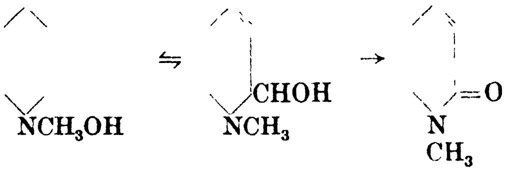
Pyridine is obtained from the "light oil" of coal tar. It is also present in bone oil. It is a liquid with a characteristic unpleasant smell.

### CHEMICAL PROPERTIES OF PYRIDINE

Pyridine and its compounds are clearly aromatic in character. Pyridine itself generally resembles benzene but is more inert. It is unattacked by hot nitric or chromic acid, and hot sulphuric acid only reacts slowly to form a sulphonic acid from which the phenolic type hydroxyl compound can be obtained. Halogens substitute in the pyridine nucleus slowly. As in the benzene series, the side chains of the pyridine homologues are oxidized to carboxylic acids. Although the diazo reaction is known for aminopyridine, it is less important than in the benzene series owing to the difficulty of nitration, and thus of preparation of amino compounds.

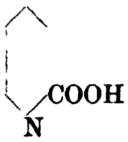
Pyridine differs from benzene in its basic reactions due to the presence of the tervalent nitrogen atom. This nitrogen atom is of the tertiary amine type, so that pyridine readily adds on alkyl halides to form quaternary ammonium type salts (pyridinium salts). The corresponding free bases can be oxidized to a ketone of the quinonoid type which is known as *pyridone.*



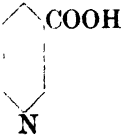


α Pyridone

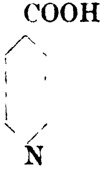
The carboxylic acids of pyridine have both acid and basic functions. The three mono acids are known as:—



α or Picolinic acid



β or Nicotinic acid

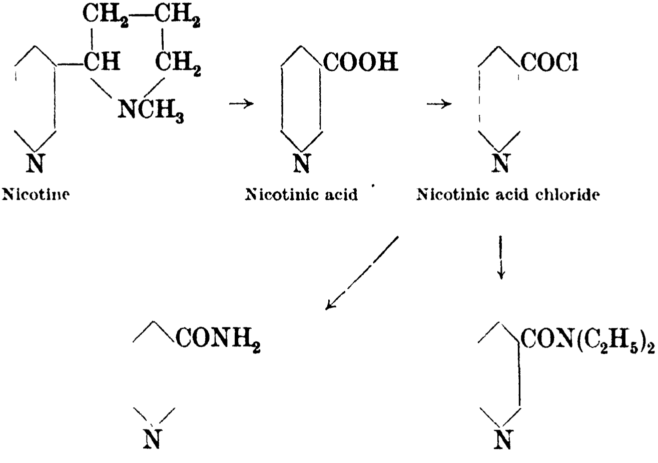


γ or Isonicotinic acid

*Nicotinic Acid* is the product of oxidation of the alkaloid, nicotine.

*Nicotinamide* is the amide of nicotinic acid and is prepared from it by preparation of the acid chloride and reacting with ammonia.

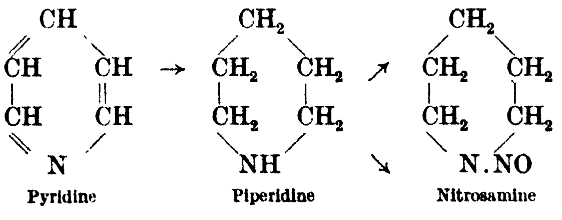
*Nikethamide* is the diethyl derivative of nicotinamide and is prepared from nicotinic acid chloride by the action of diethylamine.



Nicotine → Nicotinic acid → Nicotinic acid chloride → Nicotinamide, Nikethamide

*Iodoxyl* and *Diodone* are iodine derivatives of the quinonoid ketone, pyridone, and are prepared by the series of reactions as shown on p. 570.

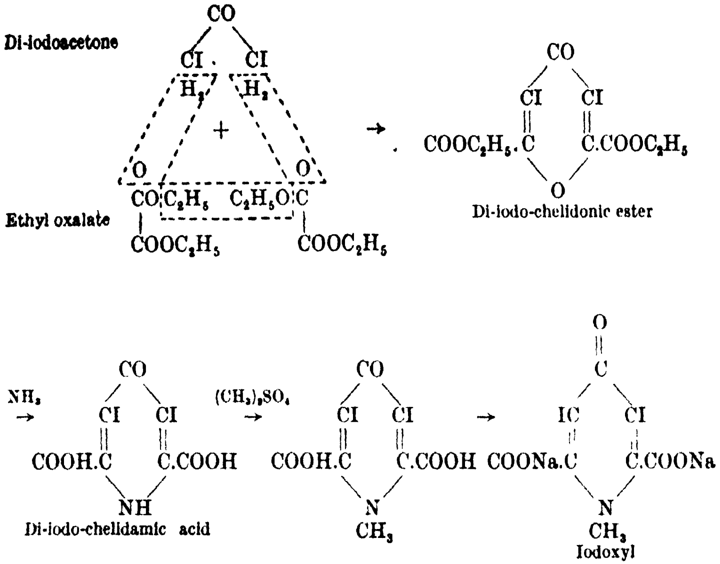
*Piperidine* is obtained by the catalytic hydrogenation of pyridine so that it bears the same relationship to that substance as does cyclohexane to benzene. Piperidine is a strong base of the secondary amine type and correspondingly it forms a nitrosamine. The piperidine ring is stable but can be opened up by oxidation, in contrast to the behaviour of the pyridine ring. Piperidine can be dehydrogenated by oxidizing agents to form pyridine.



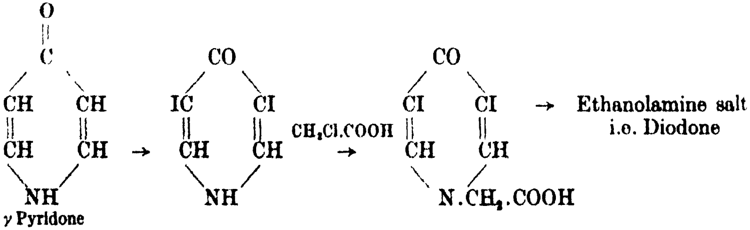
Pyridine → Piperidine → Nitrosamine

$NH_2.CH_2.CH_2.CH_2.CH_2.COOH$

Aminovaleric acid

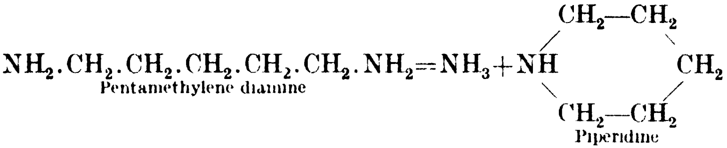


Formation of Iodoxyl

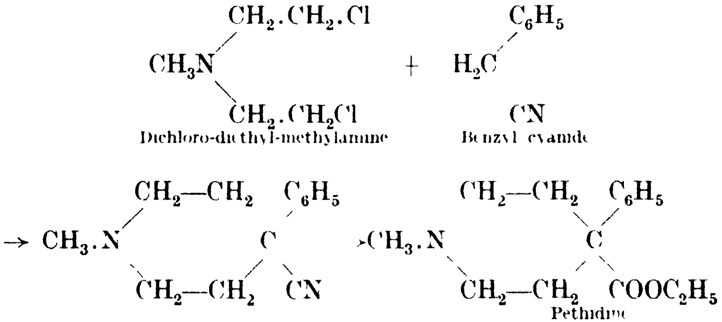


Formation of Diodone

The proof of the constitutional formula of piperidine follows from its formation by the action of heat on pentamethylene diamine.

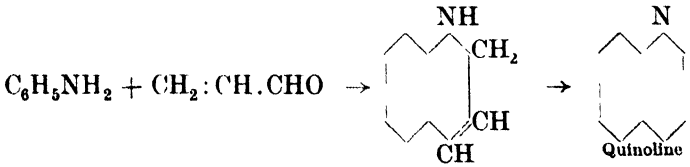


*Pethidine* is the phenyl derivative of the ester of the carboxylic acid of N methyl piperidine and is prepared by the following series of reactions.



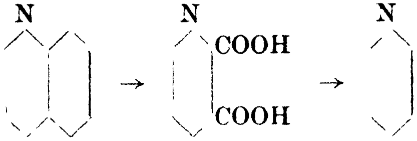
## Quinoline

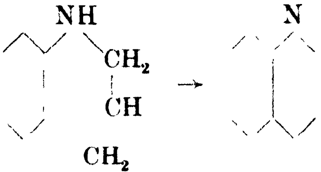
This is present in coal tar and bone oil. In the laboratory it is prepared by Skraup's reaction, which can be modified to prepare the quinoline derivatives. Aniline is heated with glycerol and an oxidizing agent (often nitrobenzene) and sulphuric acid, which acts as a dehydrating agent. This converts the glycerol into acrolein, which adds on to the aniline, forming a substance which undergoes ring closure.



## CONSTITUTIONAL FORMULA OF QUINOLINE

Quinoline is oxidized to a pyridine dicarboxylic acid, which can be converted into pyridine itself by heating with soda lime. The presence of the benzene nucleus fused on to the pyridine nucleus was proved from synthesis by passing the vapour of allylaniline over an oxidizing agent (red lead). The constitution is confirmed by the number of isomerides which are obtained on substitution (7 mono- and 21 di- of type $C_9H_5NX_2$)

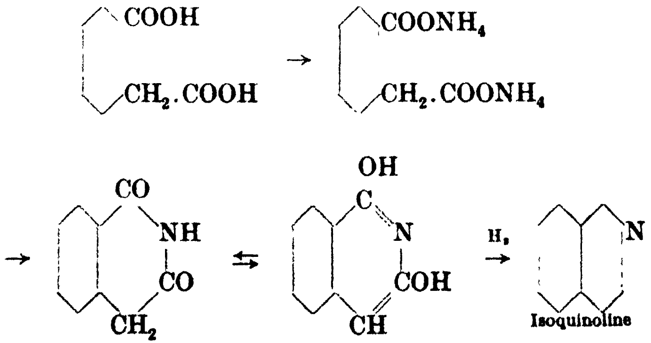




Allylaniline

### Isoquinoline

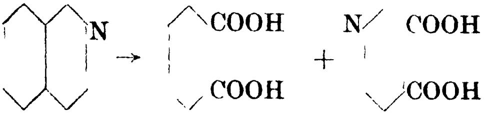
This is also found in coal tar. It can be prepared from homophthalic acid as follows



Isoquinoline

### CONSTITUTION OF ISOQUINOLINE

The constitution of isoquinoline follows from its oxidation to phthalic acid and to a pyridine dicarboxylic acid. It is confirmed by the synthetic reactions given on p. 572.

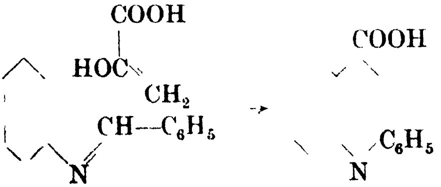


### PROPERTIES OF QUINOLINE AND ISOQUINOLINE

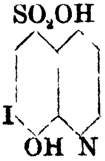
These two compounds and their derivatives resemble the corresponding pyridine compounds, e.g. they combine with alkyl halides to form quaternary salts, whose hydroxides can be oxidized to the quinolones. Nitration, sulphonation and halogen substitution take place in the benzene nucleus, in keeping with the lower reactivity of the pyridine ring. On the other hand, catalytic hydrogenation proceeds first in the pyridine ring. Isoquinoline has a more marked basicity than quinoline.

*Cincophen* is a phenyl derivative of a quinoline carboxylic acid prepared by synthesis from pyruvic acid and benzylidene-aniline.

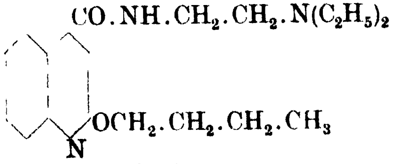
*Chionofon* is a mixture of sodium bicarbonate with the quinoline derivative of the following constitution. *Cinchocaine* is another quinoline carboxylic acid derivative.



Cincophen

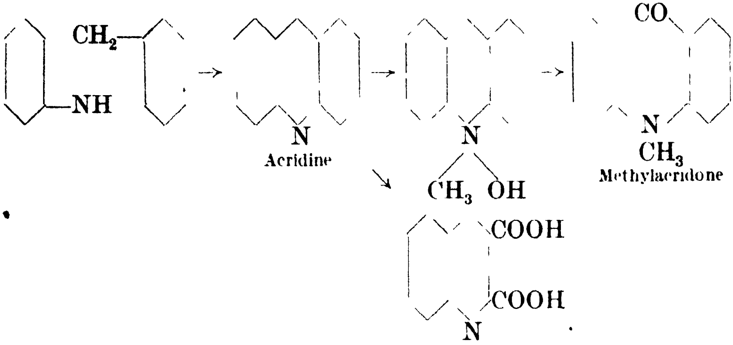


Chionofon



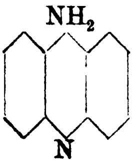
Cinchocaine

*Acridine* occurs in the anthracene fraction of coal tar and is synthesized by passing the vapour of benzylaniline through a red-hot tube. It is a stable compound with very few basic properties, but alkyl halides combine to form quaternary salts, whose free bases are oxidized to the acridones. Oxidation of acridine itself usually yields a quinoline dicarboxylic acid.

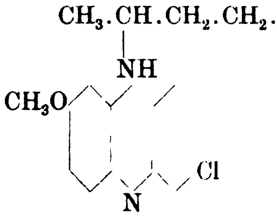


*Aminacrine* is an amino derivative of acridine and *Mepacrine* is a derivative of aminacrine.

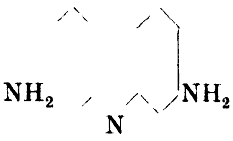
*Proflavine* is a diamino acridine and *Acriflavine* is a mixture of the hydrochloride of this diamino acridine and its methyl chloride quaternary salt.



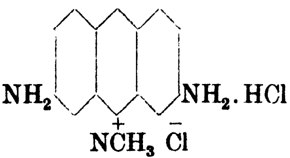
**Aminacrine**



Mepacrine

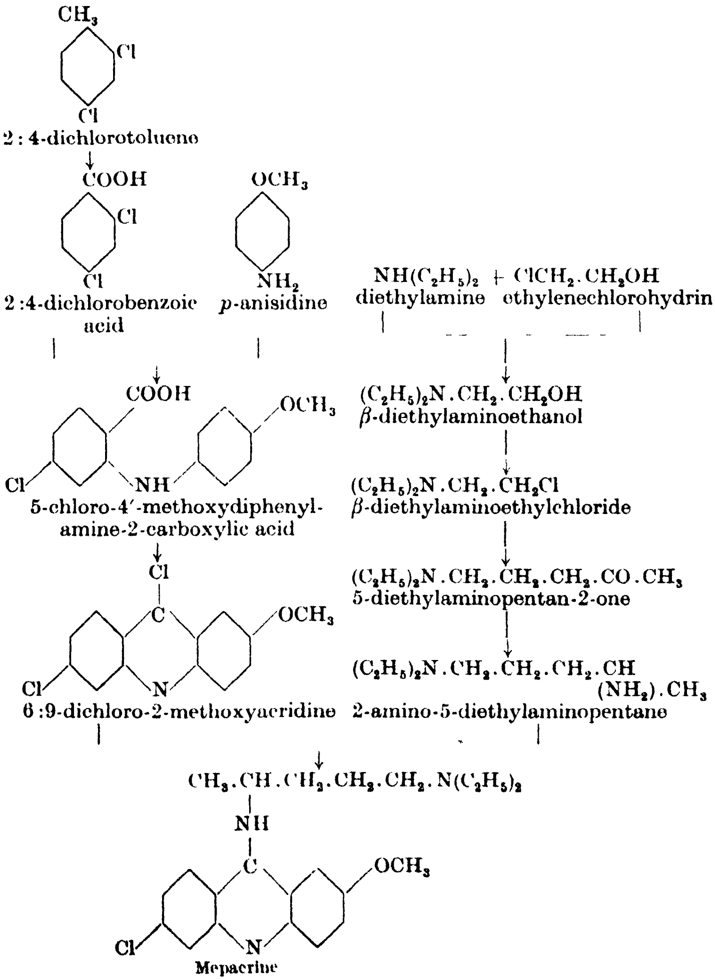


Proflavine



**Acriflavine**

Mepacrine is synthesized from benzene, toluene and ethyl alcohol by a process involving twenty-three steps. The final steps are shown in the diagram below.


$CH_3$
Cl
Cl
2 : 4-dichlorotoluene
COOH
Cl
Cl
2 :4-dichlorobenzoic acid
$OCH_3$
$NH_2$
p-anisidine
$NH(C_2H_5)_2$ + $ClCH_2.CH_2OH$
diethylamine
ethylenechlorohydrin
COOH
$OCH_3$
Cl
NH
5-chloro-4′-methoxydiphenyl-amine-2-carboxylic acid
$(C_2H_5)_2N.CH_2.CH_2OH$
β-diethylaminoethanol
$(C_2H_5)_2N.CH_2.CH_2Cl$
β-diethylaminoethylchloride
Cl
C
$OCH_3$
Cl
N
6 :9-dichloro-2-methoxyacridine
$(C_2H_5)_2N.CH_2.CH_2.CH_2.CO.CH_3$
5-diethylaminopentan-2-one
$(C_2H_5)_2N.CH_2.CH_2.CH_2.CH(NH_2).CH_3$
2-amino-5-diethylaminopentane
$CH_3.CH.CH_2.CH_2.CH_2.N(C_2H_5)_2$
NH
C
$OCH_3$
Cl
N

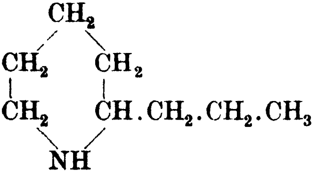
Mepacrine

## THE ALKALOIDS

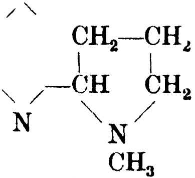
The alkaloids are organic basic substances of vegetable origin. They contain at least one atom of nitrogen in the molecule (on which their basic properties depend). Most alkaloids give precipitates with certain general alkaloidal reagents, such as tannic acid, picric acid, potassium mercuri-iodide, potassium bismuth-iodide, and solution of iodine with potassium iodide. They also give many characteristic colour reactions. Many alkaloids are derivatives of pyridine or quinoline, but others belong to chemically different families, e.g. caffeine and theobromine are purine derivatives (p. 444), ephedrine is an open chain alkaloid related to adrenaline (p. 530) and quinine, morphine, strychnine and the ergot alkaloids have very complex structures. Some typical alkaloidal formulae are given below—

$$C_6H_5.CHOH.CH(CH_3)NH.CH_3$$

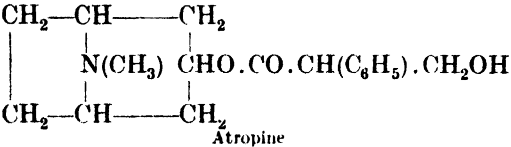
Ephedrine



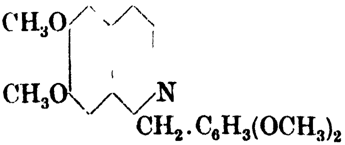
Coniine
*(Piperidine ring system)*



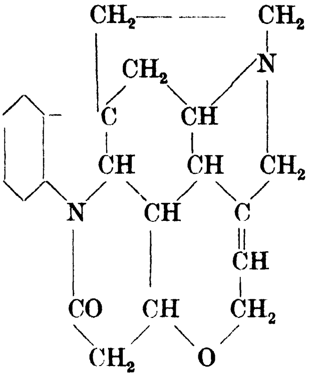
Nicotine
*(Pyridine and pyrrolidine rings)*



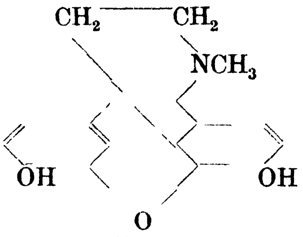
Atropine
*(Piperidine and pyrrolidine rings)*



Papaverine
*(Isoquinoline ring system)*



Strychnine



Morphine

Generally the alkaloids are sparingly soluble in water, but readily soluble in organic solvents. Their salts are usually soluble in water, but insoluble in organic solvents. (Many of the alkaloids are weak bases, so that their salts are partially hydrolyzed in solution.)

## Assay Processes Based on Extraction Methods

Organic materials, which are usually water-insoluble, organic solvent-soluble, are often separated by extraction with an organic solvent from substances which are insoluble in that solvent. This process is applied in some of the official assays e.g. Tablets of Acetylsalicylic Acid and Phenacetin. These two substances are separated by converting the acetylsalicylic acid to the sodium salt and extracting with chloroform. The salt is chloroform-insoluble, so that the chloroform extract contains only phenacetin.

Alkaloidal assay processes also depend on the relative solubility of alkaloids and their salts in organic solvents and in water; but by taking advantage of the solubility differences, it is possible to transfer the alkaloid from an aqueous solution into an organic solvent or *vice versa*.

For example, if quinine (free base) is shaken with a mixture of chloroform and water, it becomes distributed between them in accordance with the equation

$$\frac{\text{Concentration in chloroform}}{\text{Concentration in water}} = \text{constant.}$$

The magnitude of the constant is such that most of the quinine is in the chloroform layer. By separating this layer, adding fresh chloroform to the aqueous layer, and repeating, practically the whole of the quinine may be separated (cf. p. 71).

When an *acid* solution containing an alkaloid is shaken with an organic solvent (such as chloroform or ether) practically the whole of the alkaloid is extracted in the aqueous layer, since alkaloidal salts are much more soluble in water than in organic solvents. But when an *alkaline* solution containing an alkaloid is extracted with an organic solvent practically the whole of the alkaloid passes into the organic solvent layer, since the free alkaloid is more soluble in organic solvents than in water. In this way by alteration of the acidity or alkalinity of the solution, the alkaloid may be transferred from the aqueous to the organic solvent layer, and *vice versa.* These transferences enable the alkaloid to be separated from various impurities.

## The Assay of Pure Alkaloids, Alkaloidal Salts, and their Simple Solutions

The assay of simple solutions of alkaloids or alkaloidal salts, presents a comparatively direct problem. The solution is made alkaline (to liberate the free alkaloid) and extracted with an organic solvent. The alkaloid passes into the organic solvent leaving the other substances present (inorganic salts, etc.) in the aqueous layer. Thus the alkaloid is separated and can then be determined volumetrically or gravimetrically after the solvent has been removed by evaporation. In those cases where the alkaloid is a strong base and can be titrated, it is determined volumetrically by adding excess standard acid and back titrating the excess with standard alkali (using methyl red or cochineal as indicator). In other cases, the alkaloidal residue is determined by weighing.

## Assay of Crude Drugs and Galencial Preparations

### EXTRACTION OF ALKALOIDS FROM PLANT PRODUCTS

Alkaloids usually occur in the plant in the form of an insoluble salt of tannic acid or some other complex organic acid. In order to extract the alkaloid, this insoluble compound must be broken down by treatment with ammonia, lime or other substance which liberates the alkaloid base. The free alkaloid can then be extracted by some suitable organic solvent by a continuous extraction process if the alkaloid is sufficiently stable, otherwise by maceration and percolation.

The solution thus obtained contains, in addition to the alkaloid, various other substances, from which the alkaloid must be separated during the assay processes. The other substances are of three chief types: (1) resins, fats, and oils, (2) gums, sugars, and albumins, (3) colouring matter.

The first group are insoluble in water but soluble in organic solvents,* while those in the second group are soluble in water but insoluble in organic solvents. Colouring matters vary in solubility.

### SEPARATION OF ALKALOIDS FROM RESINOUS AND FATTY SUBSTANCES

If an acid solution of an alkaloid (containing the alkaloid in the form of its salt) is extracted with an organic solvent, the resins and fats are dissolved by the organic solvent while the alkaloid is present in the aqueous layer. The separation of the two solvent layers yields an alkaloidal solution free from resinous, fatty and water-insoluble colouring matter impurities.

### SEPARATION OF ALKALOIDS FROM GUMMY MATTER

When an alkaloidal solution is rendered alkaline (liberating the free base) and the solution is extracted with an organic solvent, the alkaloid passes into that solvent leaving the gummy matter in the aqueous layer. The separation of the two solvent layers yields an alkaloidal solution free from gummy, syrupy, and water-soluble colouring matter impurities.

Therefore, the alkaloid may be separated in a pure state by first acidifying the solution and extracting the alkaloid in the aqueous layer, while certain impurities remain in the organic solvent layer. The aqueous layer is then made alkaline (usually by adding ammonia), and shaken with an organic solvent into which the alkaloid passes, leaving the remaining impurities in the aqueous layer. (In a few cases, if the alkaloid is present in the preparation as an insoluble salt, it may be necessary to carry out the first extraction in alkaline solution, followed by an acid and then another alkaline extraction.) The alkaloid present in the purified extract may then be determined by the gravimetric or volumetric methods indicated above.

---

* The resin content of a drug such as Ipomœa may be determined by extraction with a suitable solvent (e.g. alcohol). After removing the solvent, washing, and drying, the residual resin may be weighed.

In practice, difficulties may arise due to the presence of emulsifying agents, the emulsification produced rendering difficult the separation of the two layer system.

## SEPARATION OF INDIVIDUAL ALKALOIDS

Many drugs and preparations contain more than one alkaloid in considerable quantity, and the different alkaloids present have different physiological effects. In these cases, it may be necessary to carry out the assay not for total alkaloids, but for a specific alkaloid. Thus, while *Aconite Belladonna*, *Hyoscyamus*, *Ipecacuanha*, and *Stramonium* are officially assayed for total alkaloids, the other official assays involve the separation of individual alkaloids from the total alkaloids extracted from the drug or preparation.

The separations are based on the physical and chemical properties of the alkaloids concerned.

Some alkaloids contain a phenolic hydroxyl group in addition to the basic nitrogen atom. These phenolic alkaloids therefore behave as weak acids as well as bases, e.g. they dissolve in 20 per cent sodium hydroxide solution. When extracted with an organic solvent in strongly alkaline solution, they remain in the aqueous layer. These alkaloids can therefore be separated from non-phenolic alkaloids which pass into the organic solvent layer.

This principle is applied in the separation of strychnine from brucine in the assay of *Nux Vomica.* Brucine, but not strychnine, is readily oxidized by nitric acid to a phenolic derivative, which is separable as above.

Other alkaloidal separations are based on the solubilities of the alkaloids and their salts in various solvents.

Morphine is a phenolic alkaloid, which is slightly soluble in water, and quite soluble in strongly alkaline (but not ammoniacal) solutions. It is sparingly soluble in alcohol-ether. In the official assay of *Opium*, the morphine is extracted in a concentrated solution of calcium hydroxide. After filtration, ammonium chloride is added to replace the calcium hydroxide by ammonia.

$$Ca(OH)_2 + 2NH_4Cl = CaCl_2 + 2NH_4OH$$

Alcohol and ether are added, when the morphine separates on standing. The other alkaloids remain in solution.

The neutral tartrates of quinine and cinchonidine are sparingly soluble in water, so these alkaloids may be separated from the other alkaloids of *Cinchona*, which form soluble tartrates. The proportion of quinine in the mixture of quinine and cinchonidine is determined by measuring the methoxyl group content, since only the first-named alkaloid contains this grouping. The separation of the other alkaloids (as in the official assay of *Totaquine*) depends on the sparing solubility of cinchonine in aqueous ether, and of quinidine hydri-iodide in water.

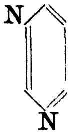
Modifications in the general technique are necessary for the assay of *Colchicum*, as the alkaloid colchicine is a very weak base. Its salts are therefore hydrolyzed, so that chloroform extracts colchicine even in acid solution. When extracted with ether in presence of a 20 per cent solution of sodium sulphate, the colchicine passes into the aqueous layer, while various impurities pass into the ether. The assay is then continued on the lines of the general procedure.

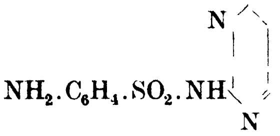
The assay of ergotoxine in *Ergot* depends upon the development of a colour as a result of a photochemical reaction (cf. p. 24) between ergotoxin and dimethylaminobenzaldehyde $(CH_3)_2N.C_6H_4.CHO$.

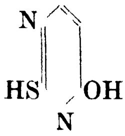
## OTHER RING SYSTEMS

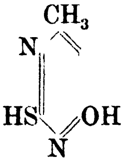
Other ring systems are found in substances of pharmaceutical importance.

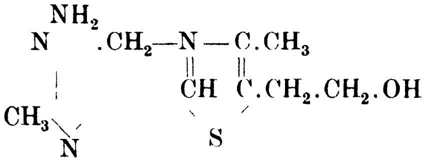
*Pyrimidine* (1.3 diazine) is present in Sulphadiazine, Thiouracil, and Methylthiouracil. Aneurine contains a pyrimidine ring and a thiazole ring.


Pyrimidine

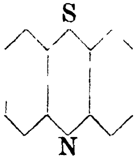

Sulphadiazine

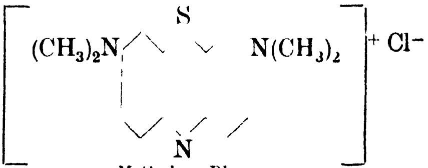

Thiouracil


Methyl thiouracil


Aneurine

*Thiazine* is present in Methylene Blue. Substances like pamaquin and penicillin and many of the alkaloids contain other ring systems.


Thiazine


Methylene Blue

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